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# Engineering technology students’ activities and learning in an electronics laboratory

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Dissertation presented in partial fulfillment of the requirements for the degree of Doctor in Science

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# Preface

When I sat down to write this part of my dissertation, sitting at the front but written only at the very end, I was wondering about the use of it. After all, it does not really contribute to the content, is full of cliches and is essentially a list of people to thank. So why not skip it? After considering it for a moment, I realised that although my name is on the front of this dissertation, it was hardly my work alone. From even before I started to (probably) years after I am done, I have met many fantastic people on the road that led to this finished study. I am truly indebted to many of them, very often way beyond the scope of the study itself. So for all of you who are mentioned below, my sincerest gratitude from the bottom of my heart.

For starters, I am very grateful to all BESTies inside and outside of EduCo, for showing me engineering education is a very valuable and interesting field to invest time and effort in. Besides these (now ex-) students, I am also indebted to all (now also mostly ex-) students who were willing to be interviewed, videotaped in a laboratory session or bothered by means of a survey or questionnaire. Probably they were gently nudged in this direction by their teachers, who were all very open to my ideas and without whom I could not have even gained access to the aforementioned students, nor to their laboratories. In no particular order, these people are Kenneth Labiau, Jan Meel, Geert Van Loock, Wei Wei, Danny Pauwels, Kristof Van Beeck, Ruben Tacq and Gorik Stevens.

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From a practical point of view, I could not have made any interviews or a video study without the equipment and advise of Johan Willems of LIMEL, nor would have been able to develop and try out a new laboratory without the equipment Patrick Baumans allowed me to play with. A huge thank you to both gentlemen. From a content point of view, I would really like to express my gratitude to the people who have been following my work from far away or up close and who have given me more than a lot of advice. I am of course talking about the members of my jury. An, thank you very much for stepping up as chair and giving a fresh eye on my work, I hope it was a bit interesting at least. Greet, thank you for helping with the access to people outside of the KU Leuven and inside of it. Mac, thank you very much for all the feedback related to the electronics-related content, as well as the grammar- and spelling-related aspects, it was a great help.

There were also people in the jury who have taken a more than casual interest in my work as members of my advisory board. Each and every one of them contributed a great deal to all stages of the project and cannot be thanked enough. Etienne, thanks for believing in the project from the start, it is very sad you could not see the end of it. Chris, thank you very much for all the help throughout the entire project, our talks at conferences, in Leuven and especially in Germany. I learned something every meeting. Wim, I am incredibly indebted to you to introduce me to all the pedagogical aspects of the study, ranging from learning theories over research methods to learning theories and back to research methods again. There would not have been a dissertation without all your invaluable feedback. Johan, thank you for bringing the more engineering point of view to the table, and especially for getting on board as my co-supervisor. It was great to have someone read through everything I wrote and to talk things through with. And last but definitely not least, my eternal gratitude to Mieke, my amazing supervisor. It is incredible how much time and effort you put into my various studies and how you (more or less) managed to cope with my engineering point of view as a die-hard physicist. As there are too many things to thank you for specifically, I will just mention one thing: thank you so much to teach me about the importance of content.

Pieter Coppens
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# Abstract

Laboratories are a staple of engineering education, as is testified by the very large fraction of face-to-face time students spend in laboratories. However, laboratories are an expensive form of instruction in terms of staff as well as equipment. Despite this important role and the high costs, research on their effectiveness is sparse. The research project described in this dissertation studies student learning in a laboratory on first order $RC$-filters. $RC$-filters are circuits the students are familiar with from introductory courses they have attended before attending the electronics course and as such serve to introduce typical concepts in electronics including frequency-domain analysis, filters, and Bode plots. Laboratories can be studied from various point of views, including in terms of so-called 'effectiveness 1' and 'effectiveness 2'. The first type ('effectiveness 1') refers to the relation between what students actually do during a laboratory session and what the teacher intended them to do during the laboratory. The second type ('effectiveness 2') on the other hand refers to the relation between what the students learn from a laboratory session and what the teacher wanted the students to learn from it. As the main interest of this research project is in the students' learning of concepts in laboratory sessions, both types of effectiveness were evaluated from this point of view.

Before analysing whether and how laboratories contribute to students' conceptual understanding, it is important to verify whether or not learning concepts is indeed a learning goal of laboratories. A first step in the research was therefore to conduct a survey among teachers and their students about the goals of laboratory education in electronics. From this, it became clear that 'learning theory' was indeed a major aim of electronics laboratories.

To gauge students' conceptual understanding, several interviews with students were conducted. From these interviews as well as earlier findings in the literature, a written questionnaire was developed to verify students' understanding of concepts related to $RC$-filters. This questionnaire then served to probe the conceptual understanding of a wider range of students than interviews allowed, as well as to track student learning by administering it as a pre- and post-lab test. The results of both the conceptual questionnaire and the interviews revealed various problems with student understanding of important concepts such as frequency-domain analysis, filter behaviour and even elementary circuit laws. These problems still persisted in the post-test.

In addition to using the conceptual questionnaire to study what students learned in the laboratory sessions, the laboratory sessions themselves were audio- and video-taped to analyse what students did and talked about in those lab sessions. To ensure a uniform and consistent analysis, a coding scheme was developed to analyse the recordings. This analysis showed that students spent most of their time gathering measurements and configuring equipment while very little time was spent analysing measurements or discussing underlying theoretical concepts. In addition, the recordings showed that students suffered from cognitive overload (because the topic, the equipment as well as the way measurements were analysed were new) and confirmation bias (because the circuit measured was known in advance).

Based on the findings of the interviews, conceptual questionnaires and video recordings, a new laboratory session was developed. The design of this new laboratory session was based on ideas from learning by inquiry and variation theory to increase the effectiveness of the laboratory session, while also reducing cognitive load and confirmation bias as much as possible. To decrease the cognitive load during the laboratory session itself, the students could practise the use of equipment by means of a simulator and the processing of measurements at home to prepare for the laboratory. During the laboratory session itself, the students were given a black box of which they had to discover the contents. This approach is inspired by inquiry learning, where the outcome of an experiment and the methodology are not known or fixed in advance. It also eliminates confirmation bias and encourages the students to process their measurement results and think about them already during the laboratory. When they found out what circuit was in their black box, they could trigger a switch that slightly altered the content of the box. They were then asked what had changed in the behaviour of the black box and what had caused this change.

The new black box laboratory was evaluated using the same methods as the original laboratory: by administering the same conceptual questionnaire before and after the lab as well as by recording the laboratory sessions themselves. The recordings indicated that students spent less time gathering measurements and setting up equipment, but more discussing their measurement results and the underlying concepts. The results of the pre- and post-test indicated no change in the students' understanding of filters or signals, however, but did show an increase in knowledge about what Bode plots were. So while the effectiveness 1 clearly increased in the black box laboratory, the effectiveness 2 did not.

The research project described in this dissertation used a variety of methods (interviews, video analysis, written tests) to verify the effectiveness of laboratory education in a specific electronics laboratory. These methods can be used in other types of laboratories to explore their effectiveness with appropriate adjustments in order to gain a broader insight into learning in laboratories. The project also revealed a difference in increase between effectiveness 1 and 2, raising the question of what the relationship (if any) is between both types of effectiveness. A last aspect that was observed informally, but not studied in depth during the project was the impact of other factors on student learning in laboratories. These factors include, but are not limited to, motivation, the content and style of lectures, student background knowledge, and relationship between pre-existing problems and learning performance.

# Beknopte samenvatting

Labozittingen spelen een belangrijke rol in ingenieursonderwijs, getuige de grote fractie contacturen die studenten doorbrengen in labozittingen tijdens hun opleiding. Labo's zijn echter een onderwijsvorm met een hoge kostprijs, zowel wat betreft onderwijspersoneel als wat betreft materiaal. Ondanks deze belangrijke rol en grote kosten, is onderzoek naar de effectiviteit van labo-onderwijs schaars. Het onderzoeksproject beschreven in deze thesis heeft als doel het leren van studenten in een laboratorium over eerste orde $RC$-filters in kaart te brengen. $RC$-filters zijn schakelingen waar de studenten vertrouwd mee zijn uit inleidende vakken die de studenten eerder gevolgd hebben en worden als dusdanig gebruikt om typische concepten uit de elektronica zoals frequentiedomein analyse, filters en Bode plots te introduceren. Laboratoria kunnen uit verschillende perspectieven onderzocht worden, waaronder zogenaamde 'effectiviteit 1' en 'effectiviteit 2'. Het eerste type ('effectiviteit 1') verwijst naar de relatie tussen wat studenten doen tijdens een labosessie enerzijds en wat de docent wilt dat de studenten doen tijdens de sessie anderzijds. 'Effectiviteit 2' daarentegen verwijst naar de relatie tussen wat de studenten leren uit een labozitting en wat docent wilt dat de studenten eruit leren. Aangezien het hoofddoel van dit onderzoeksproject het leren van concepten door studenten in labozittingen is, werden beide types effectiviteit geëvalueerd vanuit dit perspectief.

Vooraleer te evalueren of en hoe labo's bijdragen aan het conceptueel begrip van de studenten, is het belangrijk om na te gaan of conceptueel leren ook effectief een leerdoelstelling is van laboratoria. Een eerste stap in het onderzoek is daarom het afnemen van een enquête bij zowel docenten als studenten over de doelstellingen van laboratoriumonderwijs in elektronica. Hieruit werd duidelijk dat het 'leren van theorie' inderdaad een belangrijk doel is van labo's elektronica.

Om te peilen naar het conceptueel begrip van studenten, werden verschillende interviews afgenomen van studenten. Uit deze interviews en eerdere

vaststellingen uit de literatuur werd een schriftelijke test ontwikkeld die peilt naar het inzicht van studenten in concepten in verband met $RC$-filters. Deze test liet dan toe het conceptueel begrip van een groter aantal studenten na te gaan dan mogelijk via interviews en liet ook toe om het leren van studenten te volgen door de test af te nemen als pre- en post-labo test. De resultaten van zowel de tests als de interviews brachten verschillende problemen aan het licht wat betreft het begrip van studenten van belangrijke concepten zoals frequentie-domein analyse, filter gedrag en zelfs elementaire netwerkwetten. Deze problemen hielden aan in de post-test.

Naast het gebruik van een conceptuele test om na te gaan wat studenten leerden uit de laboratoria, werden de labosessies zelf opgenomen op video- en audiotape om te onderzoeken wat de studenten deden en bespraken tijdens de labozittingen. Om een uniforme en consequente analyse te garanderen, werd een codeerschema opgesteld om de opnames te analyseren. Deze analyse toonde aan dat de studenten het grootste deel van hun tijd besteedden aan het verzamelen van metingen en het opstellen van hun materiaal terwijl er heel weinig tijd werd besteed aan de analyse van metingen of de bespreking van onderliggende concepten. Daarnaast toonden de opnames ook aan dat de studenten een cognitieve overbelasting hadden (doordat het onderwerp, het materiaal en de manier waarop metingen verwerkt worden nieuw waren) en bevestigingsvooringenomenheid (omdat het circuit op voorhand gekend was).

Op basis van de bevindingen uit de interviews, conceptuele tests en video opnames werd een nieuw labozitting ontwikkeld. Het ontwerp van deze nieuwe zitting was gebaseerd op ideeën uit het leren door exploratie en variatie theorie om de effectiviteit van de labo's te verhogen en tegelijkertijd de cognitieve belasting en bevestigingsvooringenomenheid zoveel mogelijk te reduceren. Om de cognitieve belasting tijdens de labozitting zelf te verminderen, konden de studenten thuis oefenen in het gebruik van het materiaal door middel van een simulator en in het verwerken van metingen als voorbereiding op het labo. Tijdens de labozitting zelf kregen de studenten een zwarte doos waarvan ze de inhoud moesten ontdekken. Deze aanpak is geïnspireerd op het exploratieleren, waar de uitkomst van een experiment noch de methodologie op voorhand vaststaan of bekend zijn. Dit elimineert ook de bevestigingsvooringenomenheid en stimuleert de studenten om hun meetresultaten te verwerken en erover na te denken tijdens de labozitting zelf. Wanneer ze ontdekt hadden welk circuit er in hun zwarte doos zat, konden ze een schakelaar omzetten die de inhoud van de doos licht aanpastte. Ze werden dan gevraagd om uit te zoeken wat er veranderde in het gedrag van hun zwarte doos en wat deze verandering veroorzaakt had.

Het nieuwe labo met de zwarte doos werd geëvalueerd met dezelfde methodes als het originele labo: door dezelfde conceptuele test af te nemen voor en na het labo en door de labozittingen zelf op te nemen op video. De opnames gaven aan dat de studenten minder tijd spendeerden aan het verzamelen van metingen en het opstellen van hun materiaal, maar meer aan het bespreken van hun metingen en de onderliggende concepten. De resultaten van de pre- en post-test toonden geen verschil aan in het begrip van filters en signalen door de student, maar wel in hun kennis over wat Bode plots waren. Dus hoewel de effectiviteit 1 toenam in het zwarte doos labo, nam de effectiviteit 2 niet toe.

Het onderzoeksproject beschreven in deze thesis gebruikte een waaier aan methodes (interviews, video analyse, schriftelijke tests) om de effectiviteit van labo-onderwijs in een specifiek elektronica laboratorium na te gaan. Deze methodes kunnen mits gepaste aanpassingen in andere types labo gebruikt worden om hun effectiviteit na te gaan teneinde een breder begrip van leren in labo's te verkrijgen. Daarnaast bracht het onderzoek ook een verschil aan het licht tussen de toename in effectiviteit 1 en 2, wat de vraag opwerpt wat het verband is tussen beide types effectiviteit, zo er één bestaat. Een laatste aspect dat informeel werd geobserveerd maar niet expliciet werd bestudeerd, was de impact van andere factoren op leren door studenten in laboratoria. Deze factoren zijn onder andere motivatie, hoorzittingen, achtergrondkennis, en de relatie tussen eerdere problemen en leerprestatie.

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

## 1.1 General introduction

Laboratories play an important role in science and engineering education. At the Faculty of Engineering Technology of the KU Leuven for example, over 30% of the face-to-face time during the bachelor degree is spent in laboratories. The reason for this omnipresence of laboratories in engineering education is that they provide a way for engineering students to "become an experimenter," which is a fundamental aspect of "the role of a practicing engineer" [1]. Another often quoted role of laboratories is to give students a chance to "link theory to practice" [2, 3], especially in engineering education [4]. What this "link between theory and practice" precisely means is not often made explicit, although in general the emphasis seems to be on increasing the students' theoretical understanding or knowledge. This increment is then to be achieved by lab practice. So this "link between theory and practice" is a one-dimensional link where practice should lead to increased theoretical understanding. As such, more specific benefits (or goals) of laboratory instruction include making theoretical understanding better through practice; facilitating understanding of theory; and helping students to remember facts and principles [2]. Other claimed benefits of laboratories include teaching students how to properly use equipment, fostering students' enthusiasm for their studies, and helping students to learn through social interaction [2, 5]. Despite this important role of laboratories however, they are often seen as "a difficult aspect of engineering education" because of their cost [6]. Laboratories are relatively expensive compared to other, more traditional methods of teaching. One aspect that is more costly than, say, a lecture is the amount of instructor hours. A typical lecture is given in a big lecture hall with 1 instructor for around 100 or more students. During a lab session however, there is usually 1 instructor for around 20 students in a class. An other, more obvious aspect is the cost of the equipment needed in laboratories. This includes safety equipment, supplies, and of course measurement tools. Not only are these instruments and supplies often expensive, but many of these materials need to be available in multiple sets in order for students to be able to work individually or in small groups. Despite this considerable investment of both time and money in laboratories, relatively little research has been conducted on the impact of laboratory instruction on the learning of engineering students [7]. There is however, some research available about laboratories in science education. The results of these studies are mixed and are discussed in more detail in Section 1.3. Given the importance of laboratories in education and the relative lack of research about them, we decided to investigate the effectiveness of laboratories in engineering education.

As laboratories serve to “link theory to practice,” we decided to investigate the influence of the laboratories on students’ understanding of the laboratory topic. What this understanding means is explained in more detail in Section 1.5, but in short we will focus on conceptual understanding. This means not only knowing about certain laws or aspects, but also about how those relate to and interact with each other. This is contrasted with procedural knowledge, which is more about knowing how and when to perform a specific step (a calculation, configuration, $\cdots$) in a bigger context [8]. The way in which we investigated the laboratories was twofold. The first was by developing and administering a conceptual questionnaire to probe students’ understanding. The second was by observing students during the laboratory in order to pinpoint specific aspects that could possibly influence student learning. Before that, we verified whether or not conceptual learning was indeed a goal of the laboratory and we interviewed several students to get an initial idea about their conceptual understanding of $RC$-filters, the topic of the laboratories investigated.

Laboratories come in a variety of shapes and forms, most notably with respect to the topic of the laboratory session [9]. Examples in the context of engineering education include lab sessions about designing electronics, computer programming, mechanical production methods, electrical engines and many more. Not only that, but labs are taught from the first year of the bachelor education up to the final master year. This wide variety of laboratories makes it very hard to make statements about “the laboratory” in general. Therefore, we decided to focus our research on one specific laboratory session about $RC$-filters. There are several reasons for this, which are explained in more detail in Section 1.4.4. In short, there is a lot of interest in students’ elementary understanding of electricity and its governing laws in physics education research.

$RC$-filters are at the border between the type of topics in this research and the more specialised field of electronics, enabeling this work to build on existing knowledge while branching out to electronics topics. Research about student's thinking about $RC$-filters may help to uncover their thinking about these more advanced electronics concepts. As such, $RC$-filters are typically the first topic students encounter when studying electronics. They serve as a starting point to introduce important electronics concepts such as frequency domain, filtering and Bode plots. Therefore, this lab is taught in a very similar form across different campuses of the Faculty of Engineering Technology of the KU Leuven, ensuring a good research pool.

This introduction starts with a more in-depth overview of the research questions, followed by an introduction to the current research into both laboratory education and student understanding of electricity. An overview of the entire project concludes the introduction.

## 1.2 Research questions

In general, there have been some investigations into student learning in science laboratories, but not much is known about laboratories in engineering education. Similarly, much is known about student problems in electricity from a physics point of view, while very little is known about problems in electronics. This study focuses on *student learning in laboratories about electronics*. The specific topic chosen is *first order RC-filters*. This specific topic was chosen because $RC$-filters are typically the first circuits encountered in an introductory electronics course. The reason for this is that they are closely related to circuits that are familiar to the students from earlier physics courses and as such form a good transition between physics and electronics. A more elaborate overview of research in laboratory instruction is in Section 1.3, while Section 1.4 contains an introduction to the topic of $RC$-filters and the research about student understanding of related topics.

The main research question of this project is "*Does an electronics laboratory contribute to engineering technology students' conceptual understanding of first order RC-filters, and can we adjust the laboratory activities to enhance this understanding?*" This is a rather broad question that can be broken down into different components.

The first aspect of this question concerns the learning of *concepts*. As will be discussed in Section 1.5, this means that we are interested in the conceptual understanding of the students rather than, for example, in the procedural knowledge they acquire. But before verifying whether or not students gain conceptual understanding through a laboratory, one has to verify whether or not the learning goals of the laboratory include increasing students' conceptual understanding. So the first partial research question is "*What are the goals of an electronics laboratory according to teachers as well as students?*" It is important to verify not only what teachers aim to achieve with laboratories, but also whether or not the students are aware of their teachers' goals, as this awareness is a factor in the success of learning in laboratories [10–13]. This question was answered by conducting a survey with both the teachers and the students. More details are in Chapter 2.

After verifying that conceptual learning is indeed a main aim during the laboratories, the next step is to investigate the students' conceptual understanding of topics covered in those courses. This leads to the second partial research question: "*What is the nature of students' conceptual understanding of first order RC-filters?*" To answer this question, two methods were used. First, a set of semi-structured interviews was conducted with students in order to gain insight into their understanding of first order $RC$-filters in a broad way as well as to gather their opinions on the lab sessions themselves. These interviews are described in Chapters 3 and 7. Although the interviews were a good way to gain deep insight into the understanding of individual students, the findings from those particular students cannot be generalised. They are also not suitable to evaluate student learning, although they do serve to gain valuable insight into both student feelings and observations about the laboratories themselves. A method that is more suitable to both investigate student understanding on a bigger scale as well as to evaluate the evolution of students' understanding after attending a lab, is a written questionnaire. We therefore developed an open-ended questionnaire based on the student interviews as well as aspects found in literature. This questionnaire contained questions about two aspects of the laboratory on $RC$-filters that the interviewees had problems with: signals and the $RC$ circuits themselves. This questionnaire was then administered both before and (one month) after the laboratory sessions. The questionnaire itself and the students' answers are discussed in Chapters 4 (for the signal-related questions) and 5 (for the circuit-related questions).

The results of the questionnaires showed that while students had relatively little problems with certain aspects of signals, the laboratory did not help to improve their understanding of $RC$-filters or Bode plots. The latter two are topics explicitly focused on in the laboratory, so the results were rather surprising, especially when taking into account that increasing conceptual understanding is an important goal of the laboratory. It was clear that the laboratory itself should be investigated in more depth, raising the question "*What do students* *do during an electronics laboratory?*" By looking into the laboratory itself, we can see *how* the content (in this case, $RC$-filters and Bode plots) is handled and discussed by the students, leading to a greater insight into how (or whether) their understanding evolves during the laboratory. In order to gain insight into students' activities during the lab sessions, pairs of students were videotaped while performing the laboratory. These recordings were subsequently analysed by categorising both the students' activities and verbalisations. A more detailed description of the video analysis as well as the results are in Chapter 6.

The combination of the student interviews, the outcome of the questionnaire and the video study suggested several possibilities to improve the design of the laboratory, which is the last aspect of the main research question. This led to the development and implementation of a new laboratory, aimed at improving students' conceptual understanding by performing the lab activities. This new laboratory and the reasoning behind it are explained in detail in Chapter 8. This laboratory was subsequently analysed by again observing the students using video analysis and categorising their behaviour (described in Section 6.5) as well as by administrating the same conceptual questionnaire before and after the laboratories. The results of the latter are described in Chapter 9.

A summary of the answers to the research questions in the form of an evaluation of the original laboratories and a discussion of the new laboratory are in the concluding Chapter 10. This conclusion also contains a discussion of the methodologies used, as well as some suggestions for future research.

## 1.3 Earlier research about laboratories

As mentioned in the introduction to this chapter, laboratories are very widespread in engineering education practice [1]. However, little research exists that evaluates the effectiveness of those laboratories as an educational tool [10, 14]. In science education on the other hand, more effort has been put into researching laboratory instruction in a variety of fields: chemistry [15–17], biology [18] and physics [19–21]. This research is very divergent, not only in the fields that have been studied, but also in the level of the students (mostly secondary school, for example Kind et al. [22], but some about higher education even up to PhD students [19]) and the aspect of the laboratory that has been studied: its goals [4, 20, 23], the behaviour of students in the laboratory [19, 24] and the learning outcomes of laboratory work [25, 26]. This wide range of topics is interesting, but also means that there have been "relatively few systematic efforts to assess [laboratories'] effectiveness" [27]. Below, we will first discuss the research about laboratory goals. After that, we will discuss what "effectiveness" means, followed by an overview of research organised according to the interpretation of "effectiveness" used.

### 1.3.1 Research about goals of laboratory education

Before discussing the effectiveness of laboratories, it is important to establish what the *goals* of laboratory teaching are. A first important finding about goals of laboratory instruction and indeed instruction in general is that a condition for successful learning is that *students are aware of their teachers' intentions*, which is not always the case for laboratory instruction [10–13]. When the goals are not clear to the students, they have problems connecting the laboratory session with what they have done earlier in different labs or lectures. Instead of focusing on learning, students see labs as an environment in which they just manipulate equipment and gather measurements, without a connection to lectures, past and future labs, or even real world applications. Moreover, teachers sometimes do not do in laboratories what they say in advance they intend to do with them. This sends mixed signals to students who get confused about what is expected from them in the laboratory, hindering learning [28].

In the 'Labwork in Science Education' (LSE) study, teachers' goals for laboratories were evaluated in a separate report by means of a questionnaire [2]. The main conclusion from this report was that laboratories were meant to link theory and practice, to develop scientific thinking, and to develop experimental skills. The first of these, to link theory and practice, is also mentioned as a goal for learning in engineering laboratories in several other studies [3, 4, 23]. However, what this linking of theory and practice means more specifically is not explained in detail. In the LSE study, it is a header under which more specific goals such as 'making theoretical understanding better through practice', 'facilitating understanding of theory' and 'helping to remember facts and principles' are grouped [2]. This indicates that the emphasis is on the theory aspect, rather than on the practice. The practice is then the way through which better understanding of the theory is to be achieved.

In their review of research about science laboratories in secondary school, Hofstein and Lunetta argued that often the goals articulated for learning in (science) labs are not very different from those about learning science in general [10]. This raises the question of what the added value of laboratory instruction is and what specific role it plays in (science) education. In an overview of the role of laboratory instruction in engineering education published in 2005, Feisel and Rosa observed that "the literature is largely silent on the learning objectives associated with engineering instructional laboratories" [7].

They proceed to suggest that the limited amount of research in educational engineering laboratories may be due to this lack of clear objectives for laboratory instruction. They also quote an article from 1983, in which Ernst proposes three ‘roles’ of laboratories in undergraduate engineering education: to learn how to experiment, to learn new and developing subject matter, and to gain insight and understanding of the real world [6]. In addition, they refer to a list of laboratory objectives assembled by ABET (Accreditation Board for Engineering and Technology) in the early 2000s, that could be divided into three categories: cognitive knowledge (e.g. evaluating theoretical models), psychomotor abilities (e.g. to know how to use a piece of equipment) and affective domain (e.g. communication and teamwork) [5]. However, these goals were very general and “further investigation, including better segregation by discipline, is still needed” [7].

In conclusion, goals for engineering laboratory instruction are not always well defined, which makes it hard to evaluate the instruction. However, most studies seem to agree that reinforcing theoretical knowledge is a main aim of the laboratories. To verify whether or not this is indeed the case for our study, the first aspect was to verify what the goals of electronics laboratories are. This study is in Chapter 2.

### 1.3.2 What does ‘effectiveness’ mean in the context of laboratory education?

When talking about the *effectiveness* of laboratory instruction, the European ‘Labwork in Science Education’ study in the late 1990s discerned so-called ‘effectiveness 1 and 2’, which are illustrated in Fig. 1.1 [29]. That approach has later been used and developed further by Abrahams and Millar [30, 31]. This is also the main way in which we will look at the effectiveness of laboratories.

According to this framework, a first aspect to take into account when analysing the effectiveness of lab sessions is the *goal* the teacher wants to achieve. This goal is a *learning goal* for the laboratory, something the students should be able to do, understand and/or remember after following the laboratory. This can be a concept such as how a first order $RC$ filter works, but also a more practical goal such as how to conduct a certain procedure safely. This learning goal then leads to a second goal, namely what the teacher *wants the students to do during the laboratory session* itself, e.g. to measure and discuss the behaviour of said filter. Based on what (s)he wants the students to do during the laboratory, the teacher then designs the *laboratory task* for the students. This includes every aspect of the session, ranging from writing the lab manual for the students, preparing other materials, but also the behaviour of the teacher during the session itself. All these aspects are influenced by the teachers' view of the topic of the laboratory, practical constraints at the institution and the views of the teacher about learning. Based on this design of the laboratory session, the students who attend the lab will then behave in a certain way, mainly influenced by the lab design itself but also by their own view of the topic, their learning and practical constraints. If all goes well, the students will eventually reach the goal(s) set by the teacher.

The effectiveness of the laboratory session can now be interpreted in two distinct ways. The first, so-called *effectiveness 1*, is the correspondence between what *the students actually do* during a laboratory session and what the *teacher intended the students to do*. An effective laboratory in this sense is not only one in which the students manage to perform the tasks correctly and on time, but also one in which the students think and talk about what the teacher intended them to think and talk about. Abrahams and Millar make this distinction between what students are doing and what they are thinking about explicit by separating the domain of observables (objects, materials, phenomena) and the domain of ideas [30, 31], much in the same way as Tiberghien did [32]. The observables include what students are doing or talking about, while the domain of ideas is more the underlying reasons and assumptions students have that cause them to take a certain action. An inefficient lab in this sense is then one in which the students do not do what the teacher intended them to do. This does not necessarily imply that the students are wasting their time playing games or gossiping, but rather that laboratories can turn out to be different in practice than in the teachers' mind. An example is that students may find a short-cut to arrive at a solution instead of following the intended path or that one aspect of the lab takes up more time than anticipated, leaving less time for other activities. An important remark here is that it is possible that students *do* exactly what the teacher intended them to do, but do not *think* about what the teacher intended them to think about. In other words: it is possible a laboratory has a high 'effectiveness 1' when it comes to objects and observables, but a low one when it comes to ideas.

'Effectiveness 2' on the other hand refers to the relation between the intended learning goals and the eventual *learning outcomes* over a longer period of time. As such, it refers to what the students actually learn and also remember during a longer period of time after the laboratory. An example from teaching first aid is a session about cardiopulmonary resuscitation (CPR). This session is considered to have a good 'effectiveness 1' when the students perform the CPR correctly during the laboratory itself, but it is only effective in the second sense if the students still know a month later how to perform CPR correctly. It is a way to evaluate the impact of a laboratory regardless of its implementation.

Indeed, while the same learning goals can lead to very different laboratory sessions with each a very good 'effectiveness 1' (students doing what the teacher intended them to do during the laboratory), the eventual learning of the students following different laboratory sessions can be very different. In the case of the CPR, it would be possible to teach it using a special dummy that contains sensors and gives feedback to the students about the amount of pressure they apply. However, it is also possible to teach CPR by having the teacher give a demonstration and then ask the students to reiterate what (s)he was doing. Both can have a good effectiveness 1 (the students adjusting their pressure or the students answering the teachers' questions correctly), but they are clearly different approaches. Again, it is possible to separate the learning outcomes in the domain of objects and observables and the domain of ideas. Abrahams and Millar give the example of students being able to *remember and describe* what they did during the laboratory, but without showing "lasting effects [$\cdots$] on students' conceptual understanding" [30].

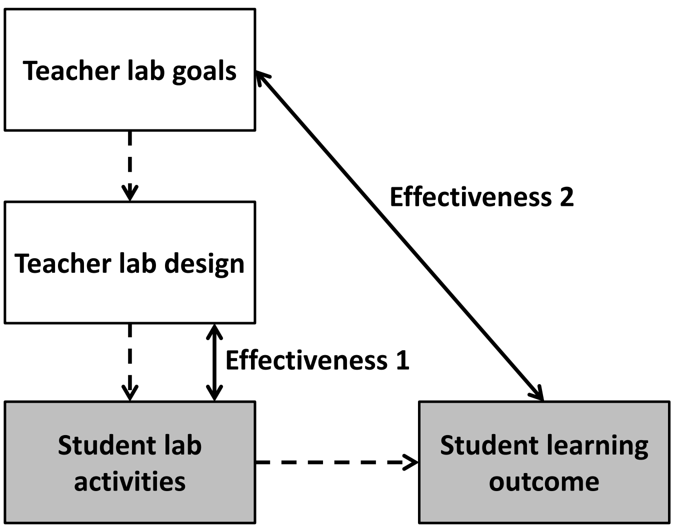



*Figure 1.1: Effectiveness 1 and 2 of a laboratory. The image is based on the 'Labwork in Science Education' project [29, 33].*

### 1.3.3 Research about student behaviour in laboratories

As discussed in Section 1.3.2, a first way to evaluate the effectiveness of a laboratory is to verify what students do and talk about *during* a laboratory (effectiveness 1). In their 1982 overview of research in educational science laboratories, Hofstein and Lunetta mentioned that "*[past research] neglected the important questions: What is the student really doing in the laboratory? And, what are appropriate ways to measure his or her activity?*" [14]. A similar sentiment was also expressed by the same RC-filters over 20 years later: "*Teachers need ways to find out what their students are thinking and learning in the science laboratory.*" [10]. In other words, more research into the 'effectiveness 1' of laboratory sessions is needed.

To assess the effectiveness 1 of a laboratory (or any other type of instruction), there are several possible methods. A first possibility is to observe the students in the lab session and make use of field notes to record what they (and their teacher) are saying and/or doing. This technique is used in, for example, pedagogical research [34–36]. This approach usually limits the analysis to one specific aspect of the classroom, for example teacher behaviour [34, 35] or student metacognition [36]. Another possible approach is to interview students and/or staff about what they think about the laboratory. We used this technique, but in a very limited way (see Chapter 7). A third possibility is to make a recording of the laboratory session and use the recordings to analyse the session afterwards. This is the approach we used in addition to the student interviews (see Chapter 6).

Not only are there many ways to analyse students' behaviour, but the laboratory is also a very rich learning environment, making it hard to study. Most researchers therefore focus on a specific aspect of the laboratory to investigate. A first example of such an aspect is the social interaction among students and between students and their teachers. This is related to the "*approaches of situated cognition and social constructivism [that] suggest that participation in communities plays an important role in learning*" [37]. As early as 1979, Kyle, Penick and Shymansky found that there were big differences (ranging from 5-30%) in the amount of time students spent interacting with (listening to) their teacher and/or fellow students in science laboratories [38]. Scherr observed four different types of social behaviour of students while working on paper and pencil exercises in small groups: individual work (limited social interaction); working together within their group; listening to the teaching assistant; and joking [39]. Warren looked at the interaction between students (and teachers) in a laboratory setting and found that the amount of interaction between two students in a pair could vary significantly between different pairs. He also observed that the importance of a student in the group with respect to sense making possibly depended on individual preferences of the students: a more shy student is less likely to voice his or her opinion than a student who 'thinks aloud', for example [40]. von Aufschnaiter also looked at students in a physics laboratory and found there were different types of interaction between students, depending on the level of complexity of what the interaction was about. She found that most interactions were so-called interaction-offers about routines and operations (e.g. student A asking student B how they should use the measurement equipment, to which student B can answer by showing how to do it) as opposed to 'explanations' which are much more abstract ways during which a student is aware of the fact that (s)he is explaining something because they understood that their colleague have a problem [37]. Ajaja focused on the behaviour of the teacher in science laboratories and found that they spent most of their time on demonstration of procedures, but also on listening to students and showing or transmitting information to them. He also found that there was a significant difference in the amount of time teachers spent on different aspects between disciplines (biology, geology, physics and chemistry) as well as between different levels of the same discipline [34]. Stang and Roll observed the interaction between students and their teaching assistants (TA) in physics laboratories and found that students were more engaged when there was more TA interaction, especially when initiated by the TA [35].

Another aspect that has been looked at is the way in which students engage with the learning material during the laboratories. A first group includes studies that focused on the measurement equipment used. Bernhard for example found that it is hard for students to use oscilloscopes, which in turn prevents them from focusing their attention on the actual topic of the laboratory [41]. Zwickl, Finkelstein and Lewandowski found that students benefited from modelling their measurement equipment while conducting an optics experiment. They found it was a "*natural way to integrate an analysis and discussion of systematic error into a lab activity*" [42]. In other words, specifically taking the equipment into account when building a model for their laboratory topic (in this case optics) helped the students to gain insight in a specific type of error. In the large-scale European 'Labwork in Science Education' (LSE) project, Niedderer et al. analysed video recordings of laboratories and found that students spent a lot of time gathering measurements, but hardly any on analysing or discussing them. They even call this a "*missing link between theory and practice*"[33]. Interestingly, this link between theory and practice is exactly what often returns when discussing laboratory goals (see Section 1.3.1). Also Roth, Mcrobbie, Campbell and Boutonné observed similar problems when looking at video recordings of students studying rotational motion [43]. Many RC-filters, including Hofstein and Lunetta in their 2004 overview, cite so-called 'cookbook-like' laboratories as a cause for students not to discuss their data [10]. In this type of laboratories, students tend to reflect very little on the set-up or the data, believing they just have to follow the instructions to get the 'right answer' [10]. This issue has been raised in laboratories across many fields of science, including electronics [44], fluid mechanics [45], biology [46], physiology [18] and physics [36]. While gathering the data, the students do not typically engage in conversation about the content of the laboratory. However, this talking about content knowledge is considered an important indication for student learning [33, 47]. Also von Aufschnaiter observed that students spent very little time on discussing physics content [19]. Lippmann and Linder focused on what students were saying and more specifically on any metacognitive statements they made. They found that not (only) the amount of metacognitive statements mattered, but rather the outcome of those statements [48]. For example, a student saying something like "this doesn't make sense" can be the start of an investigation into what is wrong and can lead the students to find the solution to their problem. However, students can also just shrug and proceed with the rest of the lab session saying they will "figure it out later at home." In short, the outcome of such video-based research is often an identification of problems with the 'effectiveness 1' of lab work, so with student activities and discussion during the laboratory sessions that do not align with their teachers' intentions for the lab. Students typically spend too much time on gathering data and too little (if any) on discussing them and/or the underlying scientific concepts (the 'theory'). While many of the studies mentioned above offer suggestions for improvement of laboratories (e.g., to include calculations or rough data analysis in the measurement process [33]), very few ideas have been tested or analysed in practice to our knowledge. An exception is the work of Bernhard and Carstensen, who have developed what they call 'conceptual laboratories' to teach students better understanding of transient response in system theory [24, 49–52] and 1D motion in mechanics [51, 53]. In those labs, technology played an important role to emphasise the critical aspects of the laboratory, e.g. by using motion detectors to immediately plot motion on a graph. Also variation theory played an important role. This approach contrasts two situations in which one parameter is changed, so students clearly see the impact of the parameter.

Even when using video recordings as a means to study student laboratories, there are still many different approaches used to analyse the recordings in the different studies mentioned above. Much of this research is done by selecting 'interesting' episodes and discussing those episodes in depth to gain an understanding of students' thinking and their reasons to take certain actions [37, 39]. While this type of analysis offers a way to gain a very detailed and rich understanding of individual students' activities, it is not suitable to compare different laboratories in an objective way. Other studies use a more rigid coding scheme to categorise student behaviour and/or conversation. This approach has the disadvantage that the information is limited in both the time domain (typically time slots are used) and the coding domain: only aspects for which a code exists can be encoded and thus analysed. On the other hand, it ensures a relatively consistent way of describing and analysing a lab session, making it possible to compare different sessions. This is also the approach used in the ESL project, where both the students' behaviour and verbalisation were assigned a specific code for each time slot [33]. Hopf used the same approach in an electricity laboratory in the 9th and 10th grade [54]. von Aufschnaiter and von Aufschnaiter used a similar approach in their study, in which they use codes to describe students' activities and what 'content area' they are engaged in at a certain point in time. In addition, they use these codes to select, transcribe and analyse specific segments in more detail [19]. Lippmann and Linder also used a rather rough coding scheme with three codes (off-task, sense making and logistics) but augmented it with an indication of metacognitive episodes [48]. Karelina and Etkina used a similar approach, although they used a more extensive set of codes and divided their metacognitive episodes into separate categories as well. In addition, their coding is done live in the lab room by taking field notes instead of using a video recording [36]. Still another approach is to use a type of network analysis, in which nodes represent different topics or people and the interactions between them are represented by arrows. An example of such an approach is the 'model for learning of a complex concept' used by Bernhard and Carstensen. In this approach, the students' knowledge (conceptual understanding) is modelled by verifying how often they make connections between different concepts during the laboratory session. The more connections there are and the clearer they are, the better the students' understanding of the topic [24, 52]. Warren used a similar technique called social network analysis, in which he categorised all student interactions with each other, the teaching assistant (TA) and the course material in a physics laboratory. This resulted in a more mathematical representation of the laboratory session as a network where the links between different nodes (the students, the TA, the material) represent interactions. By comparing the similarity (or difference) between the networks, different laboratories can then be compared [40].

As a small conclusion we can state that there is some research into the effectiveness 1 of laboratories, typically using video recordings. However, most of this research is in science education while hardly any exists in engineering education. Different methods are used to analyse the recordings, one of which is to assign a code to time slots. This is also the approach that will be used in this project (see Chapter 6). A major conclusion across these studies is that students in the studied lab settings did not talk much about content knowledge during a laboratory session. Instead, they are focused on following instructions to the letter and gathering data in order to find the 'correct answer.' The activities the students perform during the laboratories of these studies did not induce talking about conceptual knowledge very much.

### 1.3.4 Research about learning outcomes of laboratories

In addition to the research about student behaviour during laboratories, there has also been research about the learning outcomes of laboratories (the 'effectiveness 2') of labs. When discussing directions for future research in engineering education laboratories, Feisel and Rosa specifically single out "*Methods of assessing laboratory effectiveness*" as an important area for future research [7].

In science education research, a tool used to evaluate (conceptual) learning are so-called conceptual questionnaires, often used in a pre-post test design. In mechanics for example, there are the Force Concept Inventory (FCI) [55] as well as the Force and Motion Conceptual Evaluation (FMCE) [56]. Examples in the field of electricity include the AC/DC concept test [57], the DIRECT test about DC circuits [58], the Signals and Systems Concept Inventory (SSCI) [59] and many more [60].

In laboratory education, this kind of test as well as custom tests have been used to evaluate student learning. Bernhard and Carstensen used the FMCE to evaluate a laboratory on introductory mechanics, where their students showed little increased understanding after attending a classical laboratory, but more after attending a so-called conceptual laboratory [51]. Hopf evaluated a laboratory in the field of optics and electricity and found very little effect of a laboratory on students' understanding of either topic [54]. Cox and Junkin used their own test in two versions of an optics laboratory and found that students in the version where they were forced to discuss their results performed better than those who followed a more traditional laboratory [61]. Jaakkola, Nurnmi and Veermans used their own questionnaire in a small study to evaluate the evolution of children's (ages 11-12) conceptual understanding of elementary electricity topics. They found that using a simulation of circuits alone was not as helpful as using a simulation together with a physical circuit. They also found that the children benefited from explicit instruction (with the teacher explaining what is going on) as opposed to implicit instruction (where the children are left to explore by themselves) [25]. Holton and Verma used their AC/DC concept inventory to assess the effect of using a circuit simulation on students' understanding of basic electrical properties such as current and voltage. After using the simulations in individual tutoring sessions, they found it to have beneficial effects, although students still had problems when it came to aspects that were not in the time domain (e.g. frequency dependency and filtering) [62].

In addition to using specific questionnaires to test student learning in individual laboratories, it is also possible to use the final exam as a way to compare learning in different settings. An example is the recent study by Wieman and Holmes, in which they found that attending a laboratory session in an introductory physics course did not increase (or decrease) the students' performance on exam questions related to topics covered in those lab sessions compared to other questions not covered in a laboratory [63, 64].

In general, most of these studies contrast a specific type of intervention to a different one. Most often, the results are positive, although they are usually limited to a specific type of laboratory and/or student group (mostly high school students). When it comes to the influence of laboratories, the results indicate very little effect on students' conceptual understanding, although using simulations in addition to physical equipment seems to be beneficial as compared to using only one of the two.

### 1.3.5 Concluding remarks

Overall, most research on laboratory instruction so far has focused on science laboratories. Although literature suggests that one of the main aims of laboratories is to enhance theoretical understanding, the conclusions from most studies indicate that there is very little communication about content knowledge during the laboratory sessions themselves. Instead, students focus on gathering as much data as possible or on finding the 'right' answer by following their lab manual as a sort of 'cookbook'. Other research into the learning outcomes of laboratories do not suggest conceptual understanding increases after laboratory instruction either. Many RC-filters offer suggestions for improvement based on these observations, but only few have been analysed in practice. Moreover, research so far is limited to the high school level or the introductory university level. It is possible laboratories taught at higher levels of education have different goals, especially in engineering. Therefore, one of the first aspects that had to be verified was the goal of a more advanced laboratory in engineering education.

## 1.4 The importance of first order *RC*-filters

This section contains a quick introduction to the topic of first order $RC$-filters, followed by an overview of research about student understanding of electricity and, to a lesser extent, electronics. Based on this research (or lack thereof), the choice for $RC$-filters as a topic is explained.

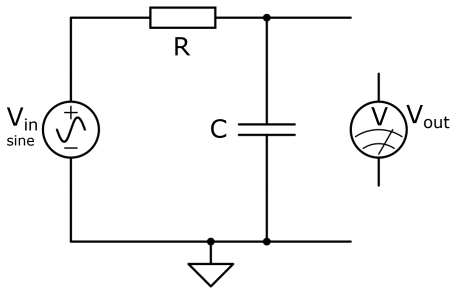
### 1.4.1 What are first order *RC*-filters?

Before discussing problems students have with electricity and electronics, an introduction into the topic of passive first-order $RC$-filters may be of interest.

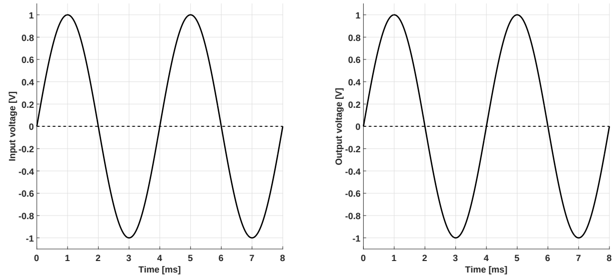
In electronics, a filter is an electric circuit that alters signals based on the *frequencies* of those signals. The discussion here is limited to passive filters, meaning they only *attenuate* signals, as opposed to amplifying them. The signals discussed are time-varying voltage signals. There are many different types of filters, usually classified according to what frequencies they attenuate. First-order $RC$-filters are either *low-pass filters (LPF)* or *high-pass filters (HPF)*. An LPF will allow a signal with a low frequency to pass undisturbed from the input to the output, but will attenuate signals with a high frequency. Similarly, an HPF will allow a signal with a high frequency to pass undisturbed, while signals with low frequencies will be attenuated. This is illustrated in Figs. 1.2 and 1.3. The careful reader may also have observed that in addition to the change in amplitude, the filters also cause a *phase shift* of the output signal with respect to the input signal when it is attenuated. This phase shift is positive for a high-pass $RC$-filter and negative for a low-pass $RC$-filter.

Signals are typically not limited to one frequency, but often contain multiple frequencies. Filters are then useful to extract the part of the signal that is relevant. An example is shown in Fig. 1.4, where a signal with two frequencies, a high and a low one, is passed through an LPF or an HPF. The LPF can be used to remove high-frequency noise from a low-frequency signal, while the HPF comes in handy to ‘straighten out’ a signal disturbed by so-called baseline wander.

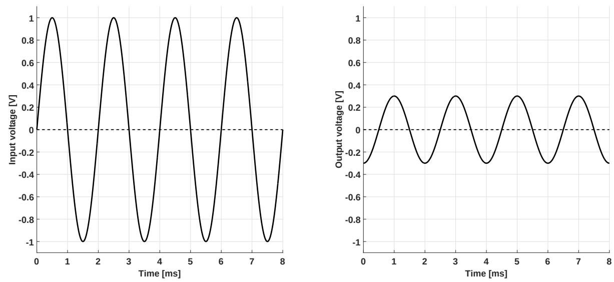
When talking about ‘high’ or ‘low’ frequencies, one has to define the boundary between both. This is most easily done by introducing another important concept in electronics: *Bode plots*. These are dual plots that both have a logarithmic horizontal axis on which the frequency of the input signal is indicated. The vertical axis then shows the gain (the fraction of the output amplitude over the input amplitude) in decibel (dB) on one set of axes and the phase shift in degrees (°) on the other. Examples for the low- and high-pass $RC$-filters are




(a) Low-pass filter



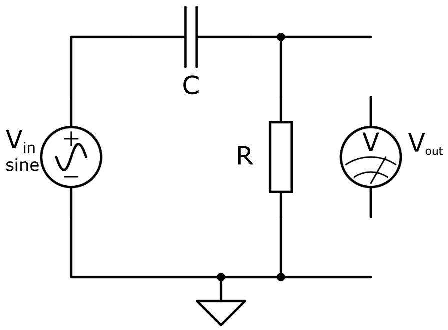

(b) Low frequency input signal (c) Low frequency output signal



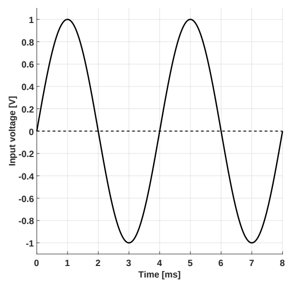

(d) High frequency input signal (e) High frequency output signal

*Figure 1.2: Illustration of the effect of a low-pass filter on signals with low or high frequencies.*

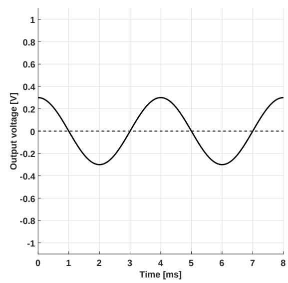
shown in Figs. 1.5a and 1.5b respectively. When looking at the phase plot, the absolute value of the phase shift for passive first order $RC$-filters is between 0° and 90°. The frequency where the phase shift is halfway between 0° and (-)90° is the *cut-off frequency* ($f_c$): the boundary between 'high' and 'low' frequencies.



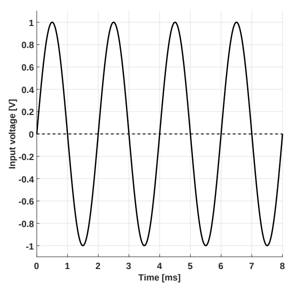

(a) High-pass filter



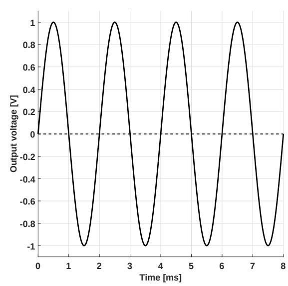

(b) Low frequency input signal




(c) Low frequency output signal



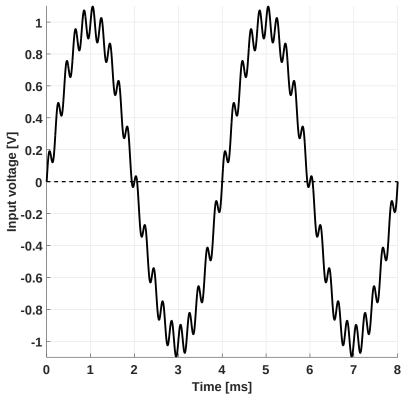

(d) High frequency input signal



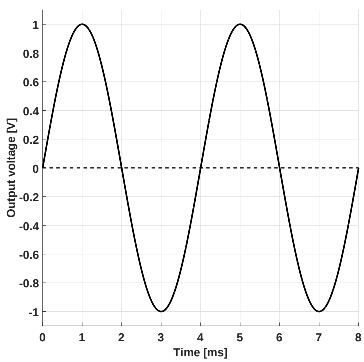

(e) High frequency output signal

*Figure 1.3: Illustration of the effect of a high-pass filter on signals with low or high frequencies.*

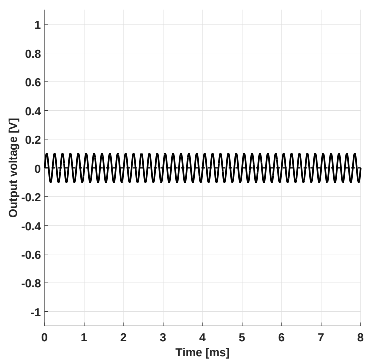
At this frequency, the gain is -3dB. This value is the point at which the power of the output signal is half that of the input signal.




(a) Signal with two frequencies



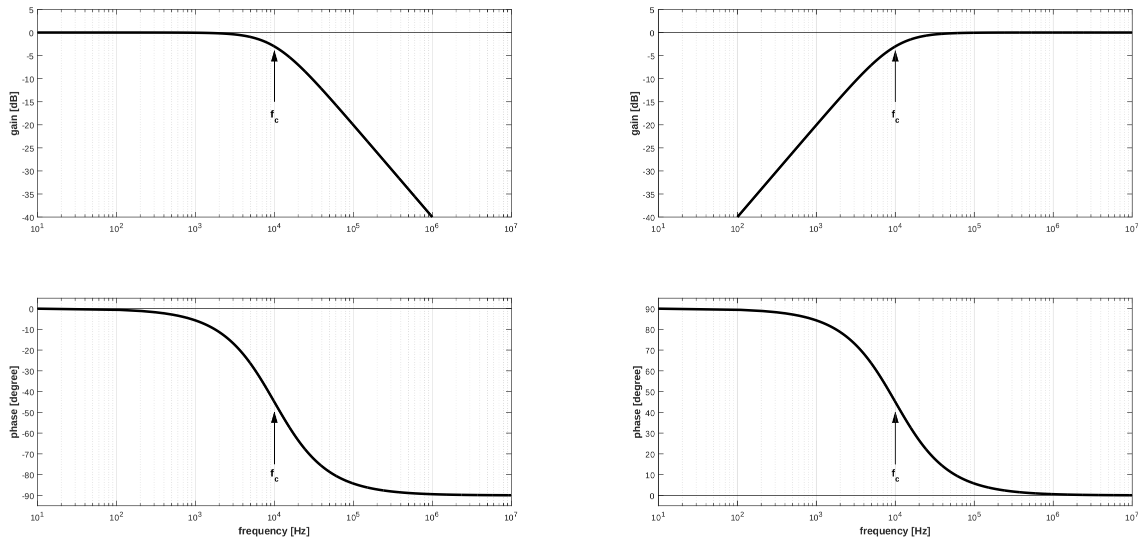

(b) LPF output signal




(c) HPF output signal

*Figure 1.4: Illustration of the effect of a low- and high-pass filter on signals with multiple frequencies. When a signal with two frequencies (1.4a) is passed through an LPF (1.2a), only the low frequency part is retained, while the high frequency is 'shaved off' (1.4b). When it is passed through an HPF (1.3a), the 'baseline wander' is removed and only the high-frequency part of the signal is retained (1.4c)*

It should also be noted that the gain for signals with a frequency greater than the cut-off frequency for low-pass filters (or lower for high-pass filters) is not infinitely small. Instead, it decreases gradually at a rate of around -20 dB per tenfold increase (or decrease) in frequency. This decrement is quantified by the *order* of the circuits: a first-order filter means that the decay in the stop-band




(a) LPF Bode plot

(b) HPF Bode plot

*Figure 1.5: Example of the Bode plot of a low- and high-pass RC-filter. The cut-off frequency, the boundary between 'high' and 'low' frequencies, is indicated by an arrow and is 10kHz in both cases.*

(the frequencies that are attenuated by the filter) is -20 dB per tenfold change in frequency (per decade). Higher order filters can have a steeper stop-band. Similarly, frequencies at the other side of the cut-off frequency still have a gain slightly below 0 dB.

In practise, the circuits discussed in the remainder of the dissertation consist of a resistor ($R$) and a capacitor ($C$). When arranged as shown in Figs. 1.2a and 1.3a, they form first-order passive $RC$-filters, explaining the final piece in the name.

In a typical introductory physics course, a DC voltage source is applied to the input terminals of the low-pass filter (Fig. 1.2a). The students then learn that the capacitor gradually charges: the voltage across the capacitor (at the output terminals) increases asymptotically to the value of the input voltage. The charging rate depends on the value of the resistor and the capacitor according to the following relation: $V_{out} = V_{in}(1 - e^{-\frac{t}{RC}})$. When the voltage source is then switched off, the output voltage decreases exponentially again. However, when the switching is done very rapidly, the capacitor does not have enough time to charge fully before starting to discharge again. When applying an AC voltage, something similar happens: the capacitor does not have the time to fully charge and as a result, the output voltage will be lower than the input voltage. The higher the frequency of the input signal, the less time the capacitor has to charge and the lower the output voltage will be. The same happens in the circuit shown in Fig. 1.3a, but now a signal with a higher frequency will pass undisturbed to the output terminals while one with a lower frequency will be attenuated. For both the high- and low-pass filters, the cut-off frequency $f_c$ depends in the same way on (only) the value of the resistor and capacitor: $f_c = \frac{1}{2\pi RC}$.

### 1.4.2 Research about basic electrical circuits

There is a lot of interest (and consequently, research) in students' understanding of electricity in the physics education research community. A full overview of everything investigated would be too much to include here, but the interested reader can find a great overview of work done in this field in the thesis of Zavala [65]. A brief summary of the most important findings regarding topics that are of interest when discussing $RC$-filters is below. These topics include students' understanding of elementary circuit laws such as Ohm's law and Kirchhoff's laws and of concepts such as current and voltage. Many of these studies employ simple circuits, typically using a battery as a DC voltage source and light bulbs as resistors.

These studies documented various misconceptions students have about electrical circuits. First of all, there are misconceptions about the concept of *current*: students think current is consumed in a circuit; that the direction of the current and the order of elements through which it flows matters and/or do not know that there can only be current in a closed circuit [66–69]. These mistakes also indicate a misunderstanding of Kirchhoff's Current Law (KCL, the 'junction rule'), which states that the sum of the currents entering and leaving a node has to be zero (essentially another formulation of the conservation of charge). Another interesting finding about current is that many students attempt to solve questions primarily by using a current-based approach as opposed to a potential-based one [68]. This current-based approach is often done incorrectly and it is sometimes not even possible to arrive at a correct answer, such as in the example shown in Fig. 1.6.

Second, many students struggle with *potential difference/voltage*: they do not distinguish between potential and potential difference; some think that voltage and current are the same or that voltage is a property of current (typically saying that voltage is defined as current times resistance); batteries are not seen as voltage sources (in the ideal case elements with a constant potential difference between both terminals) but rather as sources of constant current; difficulty in dealing with parallel branches [58, 66, 68–70]. Similar to the problems with current, these problems with voltage also indicate a problem in understanding Kirchhoff's Voltage Law (KVL, the 'loop rule') which states that the sum of all potential differences along a closed loop is always zero (conservation of energy). The students thinking the voltage across both terminals in Fig. 1.6 would become zero after removing bulb 2, clearly make this mistake. Others who thought there would be no change, also violated KVL.

Another important aspect students have problems with is *Ohm's law*. This law gives the relation between the current through a resistor and the voltage across it: $V = IR$. The underlying assumption is that for an (ohmic) resistor, the ratio of the voltage and current is a constant. This law is sometimes used when it is not applicable, most notably in the absence of a closed circuit. In that case, there cannot be any current in the circuit, but one cannot make any statements about the potential difference. However, many students think that the absence of current automatically implies an absence of voltage ($I = 0 \Rightarrow V = 0$) [67, 68, 70]. This is not necessarily the case however, for example when considering a circuit with a battery connect with one terminal to a resistor, without any connection between the other terminal and the resistor: while there is no current in this case, the potential difference between both terminals is still present. This type of flawed reasoning is referred to later in the dissertation as 'current-based reasoning' (CBR). An example is in Fig. 1.6.

Not only do students have problems with elementary circuit laws, many of them also do not understand certain aspects of physical bulbs and batteries. In addition to the aforementioned problem that students think that a battery is a current source rather than a voltage source, they fail to understand internal resistance of batteries and its implications [66, 68, 70]. Some studies have also pointed out that some perceived misconceptions may be due to students not knowing the physical lay-out of a light bulb [71, 72]. Again, Fig. 1.6 shows an example.

A final but very important problem encountered in many studies is that students not only struggle with individual circuit laws and/or elements, but also fail to reason about a circuit as a whole. This means that they often do not realise that a change at one part in the circuit (e.g. closing a switch) can have an effect on the current or voltage far away from the place where the change happens. This lack of holistic reasoning is referred to as 'local reasoning' and 'sequential reasoning' in literature [66, 68, 73, 74]. Sequential reasoning is related to the aforementioned current-based reasoning as it includes a way of "before and after" reasoning about the circuit. Students typically think current travels around the circuit and each element on its path influences it then and there. So a change at the "far end" of the circuit will not influence the current (or voltage or phase or any other aspect) until it reaches this point. Local reasoning on the other hand refers to students thinking that the current is divided into equal parts at every node, regardless of what is happening in the different branches at this node [58].

### 1.4.3 Research about more advanced circuits

In addition to the studies about resistive circuits, there have also been some studies on student understanding of circuits with capacitors and/or inductors, mainly about charging and discharging capacitors. A first observation when studying student understanding of this type of circuits was that students have difficulty with capacitors as such: students do not know what happens or what it means when a capacitor (dis)charges and have trouble understanding its impedance [57, 62, 75, 76].

Some research has been done about students' understanding of AC signals and circuits. An initial observation there is that many misconceptions discussed in Section 1.4.2 remain when discussing AC signals. Additionally, new problems specific to AC signals emerged. A first one is that students again ignore implications of KCL and KVL, but in a more subtle way: they fail to understand

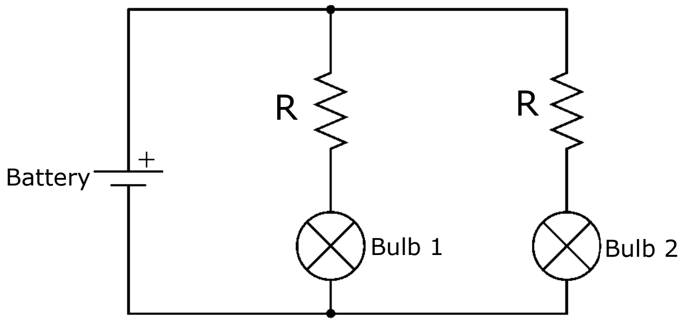



*Figure 1.6: Example of student focus on current and misconceptions about batteries. This example is from the questionnaire Cohen, Eylon and Ganiel used [68]. A battery without any internal resistance is connected to two bulbs and two resistors as shown. Both bulbs are identical, as are both resistors. Initially, both bulbs light up equally bright. What happens to the voltage across the terminals of bulb 2 when bulb 2 is unscrewed? What happens to bulb 1?*
*The correct answer is that the voltage across bulb 2 will increase (to the voltage of the battery). That across bulb 1 will stay the same and it will be lit in the same way. Many students however thought that bulb 1 would lit up brighter as now 'all the current from the battery would go to it', indicating a misconception about the battery as a source of constant current, rather than of constant voltage. Others thought the voltage across bulb 2's terminals would become zero, as 'there is no current, hence no voltage (V=IR)'. Both approaches indicate a focus on current rather than voltage in addition to other problems such as using Ohm's law inappropriately and seeing batteries as current sources. Still others thought the voltage across bulb 2's terminals would not change, despite there not being any current in that branch (and hence no voltage drop anymore across the resistor). This indicates problems with KVL (which is violated) and/or having problems in dealing with parallel branches.*

that when e.g. summing currents or voltages, one also has to take the phase into account: $A_1 sin(2\pi ft) + A_2 sin(2\pi ft + \phi) \neq (A_1 + A_2) sin(2\pi ft)$ [67, 77]. There were also specific issues with AC signals as such, including that some students think the current or voltage varies along a wire of the circuit (in space) instead of it varying in time and students not understanding what the negative cycle of an AC signal physically meant [62]. When applying an AC voltage to a capacitor or inductor, there will be a phase shift between the current through the element and the applied voltage across it. This is reflected in the complex impedance of both elements ($\frac{1}{j\omega C}$ and $j\omega L$ respectively). This fact is also troublesome to students in the sense that some think the phase shift is between the source voltage and the voltage across the circuit element [77–79]. A final issue with circuits with AC signals is that students often do not appreciate the frequency-dependency of the circuits' behaviour [57, 62].

More advanced circuits, such as those typically encountered in electronics engineering classes, are not very well researched. Some work has been done however, for example about operational amplifiers (OPAMPs) [74, 80], transistors [81, 82] and diodes [81]. This research showed that not only did students struggle with aspects specific to those topics, but they also kept struggling with the basic circuit laws such as Kirchhoff's laws and the current-based reasoning (CBR), local and sequential reasoning mentioned earlier.

When talking about AC-circuits, one of the most important parameters is the frequency of the signals. An important tool to visualise the behaviour of circuits, particularly filters, as a function of frequency are the Bode plots mentioned in Section 1.4.1. There has been some research in this field, albeit mainly from a signal analysis or system theory perspective. The field of system theory deals with the mathematical analysis and design of systems in general, independently of their physical form or shape. The research into Bode plots is so far limited to a purely mathematical evaluation of students' knowledge of their construction from a transfer function and the effect a system with a certain Bode plot has on a given signal [83–86]. Bernhard noticed that students had problems both drawing and using Bode plots when taking the final exam in control systems theory courses or analogue electronics and even considers the topic a threshold concept [83, 84]. A study conducted around 2010 by using a conceptual test about signals and systems found that students did not manage to construct a Bode plot from a transfer function and could not predict what would happen to a signal when it is passed through a system with a given Bode plot [85, 86].

### 1.4.4 The choice for *RC*-filters

Virtually all research mentioned above discusses the topics mainly in the time domain, using plots of voltage and current as a function of time. In electronics however, most of the analysis is done in the frequency domain. One of the first types of circuits students encounter in an introductory electronics course are $RC$-filters. The same type of circuit is already analysed in earlier physics courses, but is then discussed in terms of a charging and discharging capacitor in the time domain. In the electronics course however, the signals involved are AC-signals and the circuit is typically studied using a Bode plot representation. As such, these circuits serve as a bridge between physics and electronics. Not only do they refer back to earlier courses, but they serve as a vehicle to introduce many future electronics topics, including filters, circuit analysis in the frequency domain, system theory and Bode plots. The circuit itself is also used as a basis for more advanced circuits such as band-pass filters, amplifiers, differentiators etc. Despite this pivotal role in the education of (electronics) engineering students, the research of student understanding of $RC$-circuits in AC is so far limited to the phase shift between current and voltage in the circuit [77]. In addition, one question of Holton's AC/DC Concept Inventory was about a high-pass $RC$-filter (HPF), where students often mistake it for a low-pass filter (LPF) or do not appreciate the frequency dependent behaviour of the circuit at all [57]. The study presented in this doctoral thesis project aims to shed more light on student understanding of $RC$-circuits as filters as opposed to charging capacitors. In other words: from a frequency domain perspective instead of from a time domain perspective, and the transition from one to the other.

## 1.5 Learning as increasing conceptual understanding

Before doing research about learning, it is important to establish what learning means in a specific situation. In general, learning is a very complex process with many contributing factors resulting in different types of learning. In this case, we will focus on learning as an increase in *conceptual* understanding. A first aspect of conceptual understanding are the underlying *concepts* themselves. A concept is an inductive generalisation of particular instances to an abstract or generic idea. In other words, it is a general principle that underlies certain phenomena. They can take many forms, including explicit laws or definitions, but are not necessarily explicit or even verbalisable [87]. Concepts include static categories such as the idea of 'a bottle', which can mean anything ranging from an elegant, glass wine bottle to a simple plastic water bottle. But they can also be more dynamic principles, such as 'force' or 'power', which exist in very different forms and are important concepts in many domains [88]

An important aspect of conceptual understanding is the *relationship* between individual concepts. As such, conceptual understanding can be thought of as the entire web of interconnected concepts [89]. An example are laws in physics such as Ohm's law. Having gained conceptual understanding of it means not only to be able to formulate the law ($V = IR$) and perform calculations with it, but also to understand what current, voltage and resistance are as well as when it is appropriate to use the law and what its relation is with other laws. In the domain of filters, having a conceptual understanding of Bode plots for example, not only means that a student is able to sketch it based on the transfer function of the filter. It also means that (s)he is able to use it and predict what will happen to signals applied to the input; how the plot will change when an element of the circuit is adjusted; how it relates to the order of the filter; etc. This web is sometimes visualised in so-called concept-maps, used to map the conceptual understanding of students [51].

Conceptual understanding is often discussed in contrast to *procedural* knowledge, especially in the context of laboratories. The latter is knowledge of procedures, a series of steps to be followed in order to arrive at a certain goal. Procedural knowledge can be either knowledge of a predetermined algorithm that has to be executed in a fixed way to arrive at the desired result or a set of actions that lead to the goal when performed in the correct order [87, 89]. Examples of the former include medical procedures, take-off check-lists for aeroplanes and evacuation protocols in public buildings. An example of the latter are mathematical operations that lead to the solution of an equation. While each individual step of the procedure is very specific and well-defined, the procedural knowledge here also involves applying the correct rule at the correct time (and, of course, in a correct way). Procedural knowledge is then knowing when to perform a certain step for a specific type of problem. As such, procedural knowledge is not general, but rather limited to a particular set of situations in which it is appropriate. Additionally, it is also highly automated and as such requires little conscious effort. In short, procedural knowledge is *knowing how to perform a certain task*.

The reason to focus on conceptual understanding is that from earlier research, it became clear that linking theory and practice is an important goal for (engineering) laboratories (see the discussion in Section 1.3.1). The only more concrete explanation about this link between theory and practice was from the SLE project mentioned earlier. From that it seems like the link emphasises the learning of theory by means of practice, rather than, say, using theoretical knowledge to accomplish a practical goal [2].

## 1.6 Study overview

### 1.6.1 Participants and background

All students who participated in the studies that are described are students of what is now the Faculty of Engineering Technology of the KU Leuven. This is a faculty with different campuses spread across Flanders, which explains why there are different campuses mentioned in the study. At the start of the study however, this faculty did not exist yet and all campuses were individual colleges. This explains why in the earlier stages of the research (e.g. the goals study), colleges are mentioned instead of campuses. At all these campuses, the students follow the same programme within their campus during the first three semesters. This common programme differs slightly between campuses, but aims to provide the students with courses in science and mathematics, as well as an introduction into more specialised engineering fields. At all campuses, this common programme included an introductory course in electricity and magnetism. The students then choose the field in which they want to continue their studies (e.g. electronics, mechanics, chemistry or civil engineering) at the start of the fourth semester (halfway their second year).

We studied an introductory course in electronics at 3 campuses of the Faculty of Engineering Technology. At campuses 1 and 2, this course took place in the second semester of the second year, so the students who participated had already chosen to study electronics. At campus 3 however, it was taught in the first semester of the second year, so not all students would go on to graduate in electronics. As for the structure of the courses, they all consisted of a series of lectures and laboratory sessions. Typically, they had one long (2h) or two shorter (1.5h) lectures per week in addition to one laboratory session. The details of the laboratory sessions themselves are discussed in the chapter about the video analysis, see Section 6.3.2. The topics covered in the course were basic building blocks of analogue electronics (diodes, $RC$ filters, transistors, operational amplifiers (opAMPs)) and digital electronics (logic gates, flip flops, registers) as well as essential topics in both domains such as Bode plots, phase shifts, AD-DA conversion, signal sampling and binary logic. The subject of this study, $RC$ filters and, to a lesser extent, Bode plots were typically the subject of one of the first lectures and laboratory sessions for the reasons discussed earlier: the circuits are (supposedly) familiar to the students and serve as such as a way to introduce electronics concepts.

### 1.6.2 A word about the structure

The research presented in this dissertation has been partially published in various journal papers and conference proceedings. A full list of all related publications is in the list of publications, but most of them are an integral part of the dissertation in the form of individual chapters. This means that the chapters that are published papers or papers under review are meant to be readable on their own. As a result, some of the information may repeat itself, such as the description of the participants in Chapters 4 and 5. In order to keep the general structure consistent, the other, unpublished, chapters are also written in a way that makes it possible to read them independently, without the need to be aware of the entire background discussed in earlier chapters.

Of course, reading previous chapters provides more detail that may enrich the reading of subsequent chapters. These chapters have been published as journal papers or in conference proceedings, some of which use American English, while others use British English. As a result, some of the chapters also use American English while others use British English. In the chapters that have not been published, British English was used. To keep an overview of the place of each chapter in the entire dissertation, every chapter is preceded by short 'context'. In this context, the relation of the chapter with respect to the previous (and following) chapters is briefly outlined. At the end of the dissertation, the surveys used are added as appendices.

# Chapter 2

# Student and staff ideas on the goals of an electronics lab

**Context**

Before analysing whether or not students gain conceptual understanding during electronics laboratories, we checked whether the teachers' aims for such labs indeed includes teaching conceptual insight. Therefore, lab manuals were analysed and the goals stated in these manuals were studied. In all manuals, the goals were clearly formulated and conceptual understanding of $RC$-filters was mentioned as a learning goal in all of them, alongside learning how to work with an oscilloscope, and learning how to construct and read a Bode plot.

However, literature (discussed in Section 2.1) has shown that students are not always aware of their teachers' intentions with the laboratory, while there is evidence that student learning benefits from an understanding of their teachers' aim for the lab.Moreover, teachers sometimes do not do in laboratories what they say they intend to do. In order to verify to what extent students were aware of the goals of their labs, a survey was conducted among both students and teachers at the three campuses that participated in the rest of the study, as well as at one additional campus. The survey itself is added in Appendix A.

As a general conclusion, the students and teachers did agree that

> learning concepts ('theory') is indeed the most important aim of the electronics labs. So not only is conceptual understanding an intended outcome of the lab, the students are also well aware of this aim.

The details of this study are in this chapter, which has been published as

Pieter Coppens, Johan Van den Bossche, and Mieke De Cock. "Goals of lab work in electronics: Student and staff ideas". In: *International Journal of Electrical Engineering Education* 53.2 (Apr. 2016), pp. 124–136. ISSN: 0020-7209. DOI: 10.1177/0020720915598993. URL: http://ije.sagepub.com/lookup/doi/10.1177/0020720915598993.

## 2.1 Introduction

Engineering students typically spend a lot of time in the lab (around 10% at the authors' institutions), yet little research exists in this field. Although many papers use 'laboratory' as a keyword in relevant journals, most are only a description of a lab course. However, there is more literature available about labs in science education. Feisel and Rosa [7] suggest that the limited amount of research may be due to a lack of consensus on the objectives of laboratory instruction.

Hofstein and Lunetta [10] argue that often the goals articulated for learning in the lab are almost synonymous to those articulated for learning science more generally. Science education literature also shows that goals for laboratory instruction are frequently not explicitly stated, making it hard to evaluate labs [7]. Also, students are usually not aware of their teachers' intentions with the laboratory, while there is evidence that student learning benefits from an understanding of their teachers' aim for the lab [10–13]. Moreover, teachers sometimes do not do in laboratories what they say they intend to do [28].

The goal of science labs is generally to develop inquiry skills, while Edward found that in engineering, the goal is more often to integrate theory and practise (without specifying what this integration means) [4, 23]. In this paper, we do not wish to open a discussion on what the goals of lab instruction in engineering courses should be, but rather we report on a study where we tried to find out what goals are perceived important by students and teachers and whether their perceptions match. We are currently investigating how engineering students learn concepts during electronics laboratories. To make sure the labs indeed serve to teach students concepts (as opposed to, for example, procedural skills), we investigated the goals of labs in four electronics courses. More specifically, we answer the following questions:

- What goals are perceived most important by students before and after the labs?
- Is there an evolution in this perception?
- What goals are most important to teachers?
- Is there a difference between students' perception and teachers'?
- Do student ideas differ between different institutions?

## 2.2 Method

### 2.2.1 Survey

Based on literature [4, 17, 23, 91] and existing lab manuals, a survey on lab goals for an electronics lab was developed. The survey consists of a list of 17 goals to be scored on a five-point Likert scale [92] (very important to not important) and an explicit question to add extra goals if needed. To avoid participants assigning all goals the same importance, they were also asked to select the five most important goals and to rank those five goals. The full survey, including a list of all goals is in Appendix A.

### 2.2.2 Participants and course setting

The paper and pencil questionnaire was filled in by 357 second-year bachelor engineering students at four different colleges in Belgium during their lecture. They were asked to complete the survey keeping their electronics course in mind. All teachers of the different courses also completed the survey digitally. Six of the teachers were only responsible for the labs (both design and teaching), while two teachers (institutions 3 and 4) also taught the lectures.

The electronics lab sessions in the different colleges differed in terms of student population (general engineering at colleges 3 and 4 vs. electronics engineering at 1 and 2), reporting and evaluation, timing, duration and use of simulation, but the content was roughly the same for all colleges: introductory electronics. In all institutions, lab organisation was rather traditional with a detailed lab guide containing instructions both on the measurement procedures and the report. Although in all lab manuals the goals of the labs were explicitly stated, the formulation of these aims was not with respect to the lab activities in general, but rather with respect to the individual sessions. For every lab, particular goals that mainly focused on the content were formulated, such as ‘use of digital oscilloscope’ or ‘study of Bode diagram’. None of the lab manuals nor the course book or lectures contained information on the goals of the labs on a course level (as in the survey).

In colleges 1 and 2, the survey was only administered before the course started, in colleges 3 and 4 both before and after the lab sessions. Table 2.1 gives an overview of the contexts in the different colleges.

*Table 2.1: Overview of lab contexts and number of participants.*

| **Campus** | **Semester** | **Duration** | **Report** | **Simulation** | **# Pre** | **# Post** | **# Teachers** |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 2:00 | yes | yes | 144 | 0 | 3 |
| 2 | 2 | 3:00 | yes | yes | 15 | 0 | 1 |
| 3 | 1 | 1:30 | no | no | 111 | 55 | 2 |
| 4 | 1 | 2:00 | yes | yes | 87 | 55 | 2 |
| | | | | Total | 357 | 110 | 8 |

## 2.3 Analysis

As neither the students or any of the teachers added a goal to the provided list, student and staff ideas are analysed based on the Likert-scale results and the ranking of the five most important goals. In what follows, a 'group' is a cell of one of the last three columns of Table 2.1.

### 2.3.1 Scoring of lab goals

In order to obtain a ranking of the lab goals, it is possible to assign a score to every goal for a certain group in several different ways and order the goals based on that score. The possibilities for the Likert question are the following:

- Average Likert – Assign a score of 5 for a goal marked 'very important' to 1 for 'not important at all' and calculate the average
- Percentage of the group marking the goal as 'Very important'
- Percentage of the group marking the goal as 'Very important' or 'Important'.

The ranking question can be treated similarly:

- Average ranking – Assign a score of 5 for a goal ranked first to 1 for one ranked fifth, 0 for goals not in the top 5. Calculate the average.

- Percentage of the group mentioning the goal in their top-5
- Percentage of the group ranking the goal first
- Percentage of the group ranking the goal first or second.

An example of the raw data is shown in Table 2.2, showing the results for all teachers, while Table 2.3 shows the result of the ordering methods.

### 2.3.2 Comparing different scoring methods

It is clear from Table 2.3 that the different scoring methods result in very different orders, asking for a comparison between different ordering methods. This can be done in different ways:

- **Correlation** – All scoring methods result in an ordering of the goals. These different orders can be compared by computing Kendall's $\tau$ and Spearman's $\rho$ [93, 94]. These non-parametric test coefficients compare different orders instead of actual scores.
- **Student's t-test** – The distributions here are not normal (they are discrete), but since the histograms show a Gaussian distribution for all scores, this test gives a good indication of the significance of the difference between two goals for the Likert and ranking averages. Since the goals are rated by the same student, the paired version of the test is used.
- **Consistency** – To verify whether the ranking question was filled in consistent with the Likert question, every position of the ranking question was scored with a 1 (consistent) or 0 (inconsistent). The first position is consistent when this goal is also rated highest in the Likert question (not necessarily 'very important'!). Then, this goal is removed from the list of Likert questions and the process is repeated for the remaining four ranked goals. The final result for every position in the ranking question is the average (or percentage of 1s) for a group.

### 2.3.3 Comparing different groups

Comparing different groups can be done similarly to comparing different questions within a group, albeit in an adapted version:

- **Correlation** – Kendall's $\tau$ and Spearman's $\rho$ can be calculated again, but now comparing the same sorting method, but between different groups.

*Table 2.2: Detailed results for all teachers*

| | | Likert question[a] | | | | | | | | | | | | | | | | | Ranking question | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TA | **School** | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** | **O** | **P** | **Q** | **1** | **2** | **3** | **4** | **5** |
| **1** | 1 | 4 | 5 | 5 | 5 | 3 | 5 | 1 | 3 | 4 | 4 | 3 | 3 | 4 | 3 | 5 | 2 | 4 | F | C | D | O | I |
| **2** | 1 | 4 | 3 | 5 | 5 | 3 | 4 | 4 | 2 | 4 | 3 | 5 | 3 | 4 | 5 | 4 | 3 | 5 | C | Q | D | N | K |
| **3** | 1 | 3 | 5 | 5 | 4 | 3 | 4 | 3 | 3 | 4 | 4 | 3 | 3 | 4 | 2 | 5 | 2 | 4 | B | C | O | M | I |
| **4** | 2 | 3 | 5 | 4 | 5 | 5 | 5 | 2 | 3 | 4 | 4 | 4 | 3 | 4 | 3 | 5 | 3 | 5 | B | D | E | O | Q |
| **5** | 3 | 4 | 5 | 5 | 4 | 2 | 5 | 3 | 3 | 4 | 4 | 3 | 3 | 2 | 2 | 4 | 2 | 1 | B | F | C | I | J |
| **6** | 3 | 2 | 5 | 5 | 4 | 4 | 5 | 4 | 3 | 4 | 5 | 4 | 3 | 3 | 3 | 5 | 2 | 1 | O | B | C | F | I |
| **7** | 4 | 3 | 5 | 5 | 4 | 3 | 5 | 1 | 2 | 5 | 4 | 4 | 4 | 5 | 4 | 5 | 1 | 5 | C | M | O | Q | I |
| **8** | 4 | 4 | 5 | 4 | 5 | 5 | 4 | 3 | 2 | 5 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 5 | B | D | E | I | Q |

[a] A score of 1 indicates *"Not important at all"*, a 2 *"Not important"*, 3 is *"Neither important, nor unimportant"*, 4 *"Important"* and 5 *"Very important"*.

*Table 2.3: Ordering of lab goals based on different methods.*

| Order | Average Likert | | % Very important | | % (Very) important | | Average ranking | | % Ranked (general) | | % Ranked #1 | | % Ranked #1 or #2 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **C** | 4.15 | **O** | 34% | **C** | 90% | **O** | 2.28 | **C** | 72% | **O** | 29% | **O** | 40% |
| **2** | **O** | 4.05 | **B** | 26% | **J** | 80% | **C** | 2.14 | **J** | 63% | **B** | 16% | **A** | 29% |
| **3** | **J** | 4.02 | **C** | 26% | **B** | 76% | **J** | 1.98 | **O** | 57% | **A** | 14% | **B** | 29% |
| **4** | **B** | 3.97 | **J** | 25% | **O** | 75% | **B** | 1.93 | **B** | 55% | **J** | 10% | **J** | 29% |
| **5** | **D** | 3.75 | **A** | 21% | **D** | 71% | **A** | 1.69 | **A** | 46% | **C** | 9% | **C** | 24% |
| **6** | **F** | 3.69 | **D** | 14% | **F** | 63% | **D** | 1.22 | **D** | 39% | **D** | 9% | **D** | 18% |
| **7** | **A** | 3.59 | **K** | 13% | **A** | 62% | **F** | 0.72 | **F** | 32% | **G** | 3% | **K** | 8% |
| **8** | **I** | 3.56 | **F** | 8% | **I** | 56% | **K** | 0.59 | **I** | 28% | **N** | 3% | **F** | 6% |
| **9** | **N** | 3.4 | **I** | 8% | **N** | 44% | **I** | 0.57 | **K** | 22% | **F** | 2% | **E** | 3% |
| **10** | **K** | 3.25 | **N** | 8% | **K** | 43% | **N** | 0.43 | **Q** | 20% | **K** | 2% | **G** | 3% |
| **11** | **Q** | 3.21 | **Q** | 6% | **Q** | 41% | **Q** | 0.36 | **N** | 16% | **I** | 1% | **N** | 3% |
| **12** | **M** | 3.05 | **G** | 5% | **L** | 38% | **G** | 0.3 | **G** | 11% | **E** | 0% | **I** | 2% |
| **13** | **L** | 3.03 | **L** | 5% | **M** | 33% | **L** | 0.25 | **L** | 11% | **H** | 0% | **L** | 2% |
| **14** | **G** | 2.85 | **E** | 3% | **G** | 30% | **E** | 0.24 | **E** | 10% | **L** | 0% | **M** | 1% |
| **15** | **P** | 2.55 | **M** | 3% | **H** | 17% | **M** | 0.11 | **M** | 6% | **M** | 0% | **Q** | 1% |
| **16** | **E** | 2.52 | **H** | 2% | **P** | 15% | **H** | 0.08 | **H** | 5% | **P** | 0% | **H** | 0% |
| **17** | **H** | 2.47 | **P** | 0% | **E** | 14% | **P** | 0.08 | **P** | 3% | **Q** | 0% | **P** | 0% |

Pre-lab student data from institution 4 (N=87)

- **Student's t-test** – This can again only be used for the Likert and ranking averages and is now conducted between different groups for the same goal. The test is done paired when comparing pre- and post-test, while it is done unpaired when comparing different colleges.

## 2.4 Results

### 2.4.1 Ordering of lab goals

Table 2.4 shows that the correlations between the different scoring methods are very low, which could indicate they all reach different conclusions or have been filled in at random. However, the consistency is very high between the Likert and ranking question, ranging from 97% for the first item on the ranking question to 87% on the last. The reason for this anomaly is that there is not always a big difference between goals. From Table 2.5 it is clear that there are three distinct clusters. Within each one, there is no significant difference between the goals. Across all groups, there were always three clusters with the first one having approximately five goals and the last one three. When counting the number of sorting methods for which a goal is in the top 5, the results are much clearer as can be seen from Table 2.6. The same goes for the goals at the bottom, shown in Table 2.7. So, while it is not possible to make a sorted list of all the goals, it is possible to determine what group of goals is more important than the others, or which are less important.

### 2.4.2 Student ideas on lab goals

Before the labs, students find four goals very important, appearing in the top 5 for all 7 scoring methods (except institution 2):

- Illustrate the theory of the lectures (B)
- Learn the functioning of important devices (C)
- Get to know practical applications of the theory (J)
- Understand the theory (of the lectures) better (O)

At institution 2, goal C was only three times in the top 5. Instead, to "*learn how to interpret and analyse experimental data and measurements*" (D) appears seven times. It is worth mentioning goal A, to "*learn basic practical skills (such*

*Table 2.4: Correlation to compare different scoring methods.*

| | Kendall $\tau$ | | | | | | | Pearson $\rho$ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Average Likert** | **% Very important** | **% (Very) important** | **Average ranking** | **% Ranked** | **% Ranked #1** | **% Ranked #1 or #2** | **Average Likert** | **% Very important** | **% (Very) important** | **Average ranking** | **% Ranked (general)** | **% Ranked #1** | **% Ranked #1 or #2** |
| **Avg Likert** | 1.00 | 0.09 | 0.37 | 0.28 | 0.49 | -0.12 | -0.01 | 1.00 | 0.14 | 0.44 | 0.40 | 0.68 | -0.19 | 0.00 |
| **% V important** | 0.09 | 1.00 | 0.19 | 0.69 | 0.34 | 0.50 | 0.63 | 0.14 | 1.00 | 0.23 | 0.80 | 0.42 | 0.63 | 0.80 |
| **% (V) important** | 0.37 | 0.19 | 1.00 | 0.06 | 0.15 | 0.10 | 0.09 | 0.44 | 0.23 | 1.00 | 0.09 | 0.18 | 0.15 | 0.04 |
| **Avg ranking** | 0.28 | 0.69 | 0.06 | 1.00 | 0.62 | 0.40 | 0.38 | 0.40 | 0.80 | 0.09 | 1.00 | 0.70 | 0.54 | 0.58 |
| **% Ranked** | 0.49 | 0.34 | 0.15 | 0.62 | 1.00 | 0.10 | 0.06 | 0.68 | 0.42 | 0.18 | 0.70 | 1.00 | 0.12 | 0.12 |
| **% Ranked #1** | -0.12 | 0.50 | 0.10 | 0.40 | 0.10 | 1.00 | 0.57 | -0.19 | 0.63 | 0.15 | 0.54 | 0.12 | 1.00 | 0.71 |
| **% Ranked #1/#2** | -0.01 | 0.63 | 0.09 | 0.38 | 0.06 | 0.57 | 1.00 | 0.00 | 0.80 | 0.04 | 0.58 | 0.12 | 0.71 | 1.00 |

Pre-lab student data from institution 4 (N=87)

*Table 2.5: Results of Student's t-test with α=0.05 applied to goals from the same group.*

| | C | O | J | B | D | F | A | I | N | K | Q | M | L | G | P | E | H |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **C** | x | x | x | x | | | | | | | | | | | | | |
| **O** | x | x | x | x | | | | | | | | | | | | | |
| **J** | x | x | x | x | | | | | | | | | | | | | |
| **B** | x | x | x | x | | | | | | | | | | | | | |
| **D** | | | | | x | x | x | x | | | | | | | | | |
| **F** | | | | | x | x | x | x | | | | | | | | | |
| **A** | | | | | x | x | x | x | x | | | | | | | | |
| **I** | | | | | x | x | x | x | x | | | | | | | | |
| **N** | | | | | | | x | x | x | x | x | | | | | | |
| **K** | | | | | | | | | x | x | x | x | x | | | | |
| **Q** | | | | | | | | | x | x | x | x | x | | | | |
| **M** | | | | | | | | | | x | x | x | x | x | | | |
| **L** | | | | | | | | | | x | x | x | x | x | | | |
| **G** | | | | | | | | | | | | x | x | x | | | |
| **P** | | | | | | | | | | | | | | | x | x | x |
| **E** | | | | | | | | | | | | | | | x | x | x |
| **H** | | | | | | | | | | | | | | | x | x | x |

Pre-lab student data from institution 4 (N=87)
An 'x' indicates there is no significant difference in the Likert average of two goals ($p>0.05$).

*as soldering)*," which makes it four or five times to the top for all institutions.

The least important goals are harder to determine, mostly because there are a lot of 0 scores for the ranking questions. However, three of them end consistently at the bottom:

- Teach new theory (that was not addressed in the lectures) (H)
- Learn how to report orally on an experiment (P)
- Learn how to write a report about an experiment (E)

After the labs, there is no revolution at all, on the contrary. The same goals (B, C, J and O) remain at the top with goal B actually rising to the top spot for all scoring methods for both colleges, except the "% very important" at institution 4. At the bottom, the same three goals remain (P, E, and H), while "*learn how to come up with an experiment*" (G) now also emerges as an unimportant goal for both institutions.

Results show no significant differences between students across different colleges. The only issue worth pointing out is that to "*learn how to work with simulation software*" (Q) is clearly not important after the lab to the students of institution 3, while the other institutions do not see it as particularly unimportant (though

*Table 2.6: Number of scoring methods for which a goal is in the top 5.*

| Institution | Type | # | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **pre** | 145 | 5 | 7 | 7 | 2 | 0 | 2 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| | **TA** | 3 | 0 | 6 | 7 | 5 | 0 | 7 | 0 | 0 | 2 | 0 | 2 | 0 | 2 | 2 | 5 | 0 | 4 |
| **2** | **pre** | 15 | 4 | 7 | 3 | 7 | 0 | 0 | 0 | 0 | 1 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| | **TA** | 1 | 0 | 7 | 1 | 6 | 5 | 3 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 5 | 0 | 5 |
| **3** | **pre** | 110 | 5 | 7 | 7 | 0 | 0 | 2 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| | **post** | 55 | 5 | 7 | 7 | 3 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| | **TA** | 2 | 0 | 7 | 5 | 1 | 0 | 6 | 0 | 0 | 3 | 4 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| **4** | **pre** | 87 | 5 | 7 | 7 | 3 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| | **post** | 55 | 6 | 7 | 7 | 1 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| | **TA** | 2 | 0 | 7 | 7 | 6 | 3 | 3 | 0 | 0 | 5 | 1 | 1 | 1 | 4 | 0 | 5 | 0 | 5 |
| **Total** | **pre** | 357 | 5 | 7 | 7 | 2 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| | **post** | 110 | 5 | 7 | 7 | 2 | 0 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 7 | 0 | 0 |
| | **TA** | 8 | 0 | 6 | 7 | 6 | 0 | 6 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 0 | 7 | 0 | 3 |

*Table 2.7: Number of scoring methods for which a goal is in the bottom 3.*

| Institution | Type | # | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | **pre** | 145 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 7 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 7 | 1 |
| | **TA** | 3 | 5 | 0 | 0 | 2 | 6 | 0 | 6 | 7 | 3 | 5 | 2 | 6 | 3 | 3 | 2 | 7 | 1 |
| **2** | **pre** | 15 | 0 | 0 | 2 | 0 | 5 | 1 | 4 | 7 | 1 | 0 | 2 | 7 | 3 | 2 | 0 | 7 | 2 |
| **3** | **pre** | 110 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 6 | 3 |
| | **post** | 55 | 0 | 0 | 0 | 0 | 1 | 0 | 6 | 5 | 0 | 0 | 1 | 2 | 2 | 0 | 0 | 6 | 6 |
| | **TA** | 2 | 5 | 0 | 2 | 5 | 5 | 1 | 5 | 6 | 3 | 2 | 5 | 6 | 7 | 7 | 0 | 7 | 7 |
| **4** | **pre** | 87 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 7 | 0 | 0 | 0 | 1 | 5 | 0 | 0 | 7 | 2 |
| | **post** | 55 | 0 | 0 | 0 | 1 | 6 | 1 | 6 | 7 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 7 | 0 |
| | **TA** | 2 | 0 | 7 | 7 | 6 | 3 | 3 | 0 | 0 | 5 | 1 | 1 | 1 | 4 | 0 | 5 | 0 | 5 |
| **Total** | **pre** | 357 | 0 | 0 | 0 | 0 | 7 | 0 | 0 | 7 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 7 | 0 |
| | **post** | 110 | 0 | 0 | 0 | 0 | 2 | 0 | 6 | 7 | 0 | 0 | 0 | 1 | 2 | 0 | 0 | 7 | 0 |
| | **TA** | 8 | 5 | 0 | 0 | 1 | 2 | 0 | 7 | 7 | 2 | 2 | 2 | 6 | 1 | 3 | 0 | 7 | 1 |

it is not important either). As mentioned earlier, students at institution 2 find goal C less important than their colleagues and find goal D more important instead.

### 2.4.3 Agreement between students and teachers

There is a clear agreement between students and teachers about the importance of goals B, C, and O ("*illustrate lecture theory*," "*learn the functioning of important devices*" and "*understand lecture theory better*," respectively). All teachers mark these at least as "important" and/or include them in their ranking question.

This seems to indicate that the focus of both students and teachers is on learning "theory," but through devices. In other words, they want to learn the theory by doing, as contrasted to the more inquiry-focused approach often used in science labs. Similarly, they all agree with the students that goals H and P ("*teaching new theory*" and "*learn how to report orally*") are less important. The only exception is a teacher from institution 4, who found goal P "important," while his colleague (from the same institution) found it "not important at all." None of the teachers included these goals in their ranking question.

### 2.4.4 What teachers find important, but students do not

Goals F ("*learn measuring techniques*") and I ("*learn how to handle measurement results critically*") are considered "(very) important" by all teachers, making it often to their ranking top-5. However, none of the students find those important.

Goal D ("*learn how to interpret and analyse experimental data and measurements*") is also deemed "(very) important" by all teachers, who often include it in their ranking top-5. Only the students at college 2 recognise the importance of this goal to their teacher, while the students at none of the other colleges agree.

Goal Q ("*learning how to work with simulation software*") is considered important by all teachers of colleges 1, 2 and 4, while their students do not find it an important goal at all. On the contrary, it even shows up at the bottom 3. At college 3, simulations are not required, making it plausible that teachers indicate the goal as "not important at all" and students do not see it as a priority either.

It is also worth mentioning goal E ("*learn how to write a report about an* *experiment*”) in this list. The students’ opinion is clear on this: it is not important. However, teachers disagree, sometimes even within one institution. It is clearly important at institution 2, not really a topic at college 1 and the role of written reporting according to teachers is unclear at colleges 3 and 4.

### 2.4.5 What students find important, but teachers do not

This category has two goals:

- Get to know practical applications of the theory (J)
- Learn basic practical skills (such as soldering) (A)

Goal J is mostly considered “important” by teachers, but it is only once included in the ranking top-5 for teachers. So while it is important to teachers, it is not as high a priority as students believe it to be. Goal A on the other hand is clearly less important to teachers, never making it to the ranking top-5 and never marked as “very important.”

## 2.5 Discussion

There is not a lot of difference between different institutions, for neither teachers nor students. There are two exceptions: at institution 3, there are no simulations required, while they are at the other ones; only the students at institution 2 realise the importance of properly “*interpreting and analysing data*.”

According to Berry et al., students agreeing with their teachers’ expectations can benefit in their learning [12]. Although students and teachers agree on some of the most important and unimportant goals, there are still some goals students don’t seem to find as important as their teachers do.

It is remarkable that students’ ideas do not substantially change after they followed the labs, especially about writing a lab report: students are graded based on their reports in three institutions, but even after the labs they do not find learning how to write a report important. It might be that students do not see ‘writing a lab report’ as a major goal of the labs, as the labs as they are organised do not provide a lot of support to learn how to do it. Although students are required to hand in a report and they are graded based on the reports, the lab manuals do not contain information on what is considered to be a good report. Moreover, only in one institution do students get feedback on their report, but this feedback mainly relates to technical aspects (use of LaTeX). Similarly, it is striking that they do not find it important to learn how to measure correctly and how to process these measurements. Despite their teachers finding this important, only the students at college 2 seem to realise the importance of correct measurements, although even they do not recognise the importance of processing them properly. Finally, students do not seem to find it important to learn how to use simulation software, while this is an important topic in the labs of three of the four institutions.

The most obvious conclusion, however, is that both teachers and students see the lab as a means to increase the student's theoretical understanding, with the caveat that the theory should not be new.

This is in clear agreement with Edward [4], although it remains to be seen whether or not this goal is actually achieved, given the mismatch between some of the goals and earlier research pointing in the opposite direction [4, 33, 95].

# Chapter 3

# Student Understanding of Filters in Analog Electronics Lab Courses

## An interview study

### Context

After establishing that learning conceptually about first order $RC$ filters is indeed an important learning goal of the laboratory, we wanted to gain insight into the students' understanding of this topic. To explore students' ideas about first-order $RC$-filters as broadly as possible, a series of student interviews was done at the beginning of the study. All these interviews were conducted with volunteers from campus 1 and were held approximately one month after they had attended the lab on $RC$-filters. The interviews were semi-structured and probed students about various aspects of filters, including signals, circuit laws and use of filters. The participating students displayed many misconceptions and problems, some of them known from literature but others novel. One of the most striking problems was the difficulty the students had with Bode plots, a representation that is essential in electronics and in particular when studying filters. A year later, 7 more students were interviewed in the same manner with similar results. In addition, those students answered questions about the laboratory session itself. The results of those are discussed in a later chapter (Chapter 7).

The interviews and their results have been presented at the 40th SEFI Annual Conference in Thessaloniki (Greece) in 2012 and the text has been published in the proceedings of the conference as:

Pieter Coppens, Mieke De Cock, and Christian H. Kautz. "Student Understanding of Filters in Analog Electronics Lab Courses". In: *40th SEFI (Société Européenne pour la Formation des Ingénieurs) Annual Conference:Engineering Education 2020: Meet the Future*. Ed. by Aris Avdelas. Thessaloniki: SEFI-Société Européenne pour la Formation des Ingénieurs, 2012, pp. 196–197. URL: http://www.sefi.be/conference-2012/Papers/SEFI%20Book%20complete.pdf.

## 3.1 Introduction

Physics Education Research has helped to identify many student difficulties with specific concepts in introductory physics. Results from several studies that focus on specific topics support some general conclusions on teaching and learning of physics that by now are widely accepted [97, 98]. Moreover, there is a growing research base on upper-division physics courses. Many (introductory) engineering courses cover topics in which basic physics principles are applied or extended. It therefore seems plausible that methods from PER could be applied to investigate student understanding in these engineering courses. Analog electronics is such an example, which uses and extends principles typically covered in an introductory Electricity and Magnetism course. Although there is extensive research on conceptual difficulties with basic electric circuits [25, 58, 66, 68, 71, 99–104], very little is known about student understanding of more advanced electronics concepts [80, 81, 105, 106].

Recently, we have begun an in-depth investigation of student conceptual understanding and student learning in upper-division electronics lab courses for engineering students in order to get a detailed understanding of what students actually learn and how students develop an understanding of concepts during the lab sessions.

Filters is one of the canonical topics covered in most of these courses, and is also dealt with in the lab. As a starting point, interviews were carried out to probe student understanding of first order passive $RC$-filters. Preliminary results are presented: we will discuss common difficulties that were elicited during the interviews and examples of student reasoning.

## 3.2 Literature review

Student difficulties and conceptual understanding in electricity and electric circuits have been studied extensively [25, 58, 66, 68, 71, 99–104]. A substantial amount of this research has been carried out at the secondary school level, but there also have been investigations of introductory university courses, both for technical and non-technical careers.

Most of the work so far focuses on student ideas about DC circuits [58, 66, 71, 100, 102–104], with few studies about AC circuits [62, 67, 77, 82]. However, we do expect some of the difficulties observed in this context to be also relevant for the understanding of more advanced electronics topics such as first order passive $RC$-filters.

Possibly relevant concepts, and the corresponding student difficulties in DC circuits that have been identified, include:

- *Current*: Students often confuse current with voltage and have difficulties with the physical interpretation of moving electrons. Current is frequently thought to be 'consumed' [62, 100].
- *Voltage*: Students have problems with applying Kirchhoff's voltage law and think that there can be no voltage without current [67, 83, 100].
- *Resistance*: Students don't seem to grasp the physical interpretation of a resistance, thinking more current means more resistance and confusing series with parallel. As a consequence, they have problems interpreting Ohm's law [62, 68].
- *Sequential reasoning*: Students fail to see the circuit as one entity. Instead, they analyse every component separately while 'going around' the circuit [77, 99, 100].

Recent research on more advanced AC sources shows that students have difficulties with phases, that they do not fully understand the physical meaning of the mathematical description and that they do not always understand the frequency dependence of the impedance [62, 77]. Concerning more advanced electronics topics, only very little research has been published [80, 81, 105, 106].

## 3.3 Method

We recruited 4 students from the $2^{nd}$ year of a bachelor degree in industrial sciences, option ICT-Electronics. All students were male. Students were solicited for these interviews via course email near the end of the semester and were given a small gift in recognition for their time and effort. They had had a laboratory session on 1st order $RC$-filters one month prior to the interview. Participants, in advance, were unaware of the exact content of the interview, which was semi-structured and lasted for about 30 minutes. All were both video- and audiotaped and notes that the student made on flipcharts were kept for analysis. The recordings were transcribed for later analysis.

The interviews we conducted were aimed to get a first insight in the understanding of basic $1^{st}$ order $RC$-filters by undergraduate electronic engineering students. Students were asked to explain the working of filters: an interview protocol was developed, serving as a loose guideline for the interviewer. Questions probed general understanding in 4 main categories. The first part was about the concept of a filter, to see if students understood its use. A second part probed the understanding of the physical working principle behind a basic filter. The third part went deeper into the operational functioning of the device, asking the students to draw current and voltage graphs. To conclude, we asked the students some design-like questions, such as how to turn a low-pass filter into a high-pass filter or the other way around. Students were not told whether or not they answered a question correctly during the interview session.

After the interviews, the recordings (including partial transcriptions and the written records produced by the interviewees) were used to critically assess the students' answers to our questions. In doing so, we not only checked for the correctness of their answers but also tried to gauge whether their reasoning was sound and reflected correct use of the underlying concepts and principles. In case of incorrect answers, an effort was made to reconstruct the student's mental images that led him/her to this answer. Our intent is to correctly reproduce the students' (possibly flawed) logic as a starting point for the development of instructional materials that help students overcome their incorrect conceptions.

## 3.4 Results

Many misconceptions documented in the literature showed up during the interviews, while we also encountered some new problems. However, as this is based on only 4 interviews from one institution, the results should be seen as preliminary findings, with no claim about generality. In the following, excerpts of the interviews are used to illustrate typical student mistakes. Student names are pseudonyms.

### 3.4.1 Current-based reasoning

As stated in section 3.2, previous research indicates that students often reason about circuits based on current alone. In our interviews, only one of the students, Jack, managed to link the impedance of the capacitor via Ohm's law and Kirchhoff's voltage law (KVL) to the output voltage. He made the drawing of a high-pass filter in Figure 3.1a and gave the following explanation, which we include here as an example of correct reasoning.

INTERVIEWER: You said you charge it, the capacitor. How exactly does that have an influence on the output?

JACK: At a low frequency, so also a low angular frequency $\omega$ (points at formula $\omega = 2\pi f$), we have a big impedance (points at formula $Z_c = 1/(j\omega C)$), which causes a big voltage drop across it. Well, a big voltage over (points at capacitor in the circuit ). And a bigger voltage over here, Kirchhoff's law, the loop-law, makes that here (points at resistor in circuit) there is a small voltage. And if we have a large angular frequency, so a small impedance (points at formula $Z_c = 1/(j\omega C)$), a small voltage across the capacitor (points at capacitor in circuit) and a bigger voltage across this resistor (points at resistor in circuit), which means we get a big signal.

The other three students did not manage to correctly analyse the circuit: they reasoned mostly based on current, ignoring the fact that both the input and the output signal are voltages, not currents. This is shown in the reasoning of Jeff, who had drawn the circuit of a low-pass filter (see Figure 3.1b). However, in the following quote, he describes it as a high pass filter (calling it a "*low frequency filter*"):

JEFF: (draws circuit of low-pass filter, as shown in Figure 3.1b)

INTERVIEWER: Ok, so you said earlier they [filters] could either allow low or high frequencies to pass. Which one is this one?

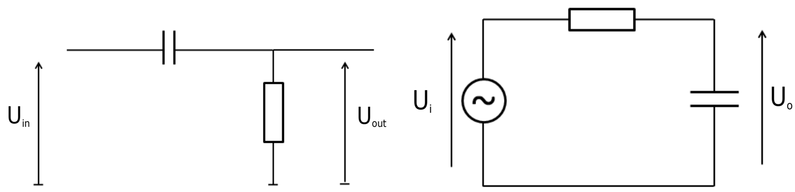
JEFF: I think the high ones, but I'm not completely sure.

INTERVIEWER: So you say that the circuit there will allow signals with a high frequency to pass and not the ones with a low frequency. Can you explain why it is that it [the capacitor] has an influence?

JEFF: That your capacitor, it will $\cdots$ because it $\cdots$ can be considered to be an open circuit at err, low frequencies, it won't allow it [the low-frequency signal] to pass in any case and so well, it will $\cdots$ it's a low frequency filter.

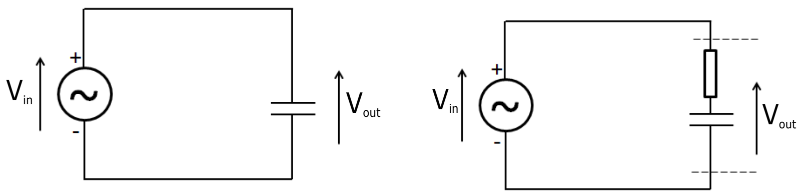
### 3.4.2 Difficulties with potential

Related to this current-based reasoning is a poor understanding of potential difference. Three students showed problems with it, albeit in different ways. One student (John) used only a capacitor to serve as a complete filter, directly




(a) (b)

*Figure 3.1: Fig. 3.1a shows a high-pass filter as drawn by Jack, while Fig. 3.1b is a low-pass filter drawn by Jeff, who claims that it is a high-pass filter.*




(a) (b)

*Figure 3.2: Fig. 3.2a shows a low-pass filter according to John, while Fig. 3.2b shows how John still shortens input and output after adding a resistor.*

connecting the input and output (see Figure 3.2a). He still claimed the input and the output to be different, despite the short. Even later on, when a resistor was added to the circuit (Figure 3.2b), he said the output voltage was to be measured across both the resistor and the capacitor:

JOHN: (adds resistor Figure 3.2a, resulting in the circuit of Figure 3.2b)

INTERVIEWER: Wait, so what is your $V_{out}$ in this case?

JOHN: Wait, is then with the … with the resistor (draws horizontal dashed lines in Figure 3.2b) Then it's here, yes, here.

When talking about low-frequency signals, Jeff correctly replaced the capacitor in Figure 3.1b by an open circuit. He correctly stated there was no current, but also assumed this meant there was no voltage at the output, indicating that he thinks voltage is caused by current:

INTERVIEWER: Can you draw me again your input signal and your output signal?

JEFF: (sketches a sine wave) The input will simply be something like this, but there won't be an output anymore.

INTERVIEWER: And what do you mean by "won't be there?" What if you attached a voltmeter for instance ?

JEFF: That's an open chain and then there is no current through the circuit and then there is no voltage between [the output terminals] anymore.

For both of these students, Jeff and John, the basic principle of a high-pass filter seems to be to prevent low-frequency currents from flowing (as a result of a high impedance at these frequencies). Their reluctance to recognise voltage as the quantity through which the input and output of signals occurs may be related to difficulties with Kirchhoff's voltage law and the concept of potential. This misconception also appears in [67].

### 3.4.3 Lack of conceptual understanding

The tendency of students to memorise formulas without a conceptual understanding of the physical background also became apparent during the interviews. Every student wrote down the formula for the impedance of a capacitor immediately when asked to explain its influence on the behaviour of the circuit as a filter. They were aware of the mathematical implications of the formula (e.g. they understood that an increase in frequency or capacitor value decreased the impedance) but could not relate it to the physical working of a capacitor.

Three of the students came up with the time constant when asked to provide more detail. Two of them remembered the correct mathematical expression, but were unable to relate it to the frequency-dependent behaviour of a capacitor. Jeff stated that a certain circuit had "*a higher time constant, so it takes less time for the capacitor to charge.*" John also first said that a higher time constant resulted in faster charging, but he corrected himself a few minutes later. As mentioned above, he had previously omitted the resistor from his circuit diagram (Figure 3.2a), claiming that a resistor was only needed to calculate the time-constant. Apparently, he thinks of the time-constant as ultimately a "*property of just the capacitor and the resistor is not present here [in a filter].*"

When asked what would happen if the capacitor value would double, all interviewees said that it would have an influence on the cut-off frequency, although only one (John) gave a correct reasoning. However, when asked what would happen when the resistance would double, two of the four students claimed it would not have any impact on the behaviour of the circuit at all. None of the students was able to explicitly link the time constant to the cut-off frequency of the filter.

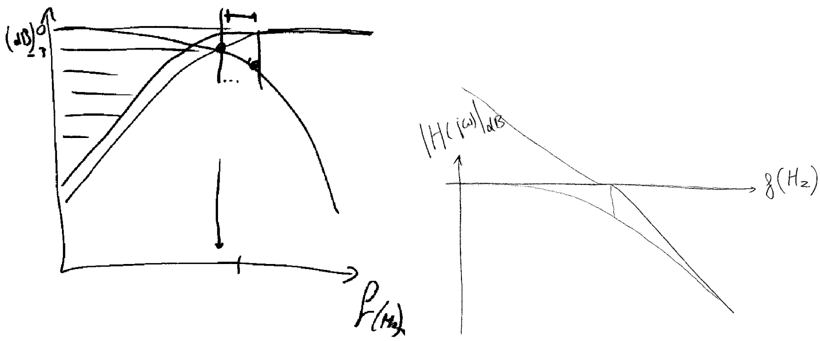
### 3.4.4 Difficulties in frequency representation

Only two of the students managed to draw a correct gain diagram, but only James seemed to have fully understood its meaning. He was able to change the cut-off frequency, draw the curve for a low-pass filter as well as use it to indicate how to create a band-pass filter. His drawing is shown in Figure 3.3a. The other student, John, had problems drawing the Bode diagram of a high-pass filter, after he had correctly made one for a low-pass filter. As is shown in Figure 3.3b, he actually sketched a curve corresponding to a low-frequency amplifier.

In [83], Bernhard and Carstensen categorise the Bode plot as a so-called threshold concept. This implies that, once this concept is understood, learners have a better understanding of (in this case) filters in general. Because of their claim, we paid special attention to this representation. As the one student who seems to have achieved greater facility with Bode plots was also more proficient concerning other aspects of filters, our results thus far could be interpreted to be in agreement with their assertion. A greater number of interviews, and a more in-depth analysis of the students' reasoning about Bode plots would be required to substantiate the claim that Bode plots indeed form a threshold concept, thereby implying a causal relationship between a student's understanding of this and other concepts.

### 3.4.5 Phase shift between input and output

Only one student (Jeff) took the phase shift between the input and the output voltage into account when asked to draw the output voltage in the suppressed part of the spectrum. Even so, he didn't know how much the phase shift was exactly and he couldn't explain why this happened and thought it was always the case, regardless of the frequency. All the other students did not seem to recognise that such a phase shift could occur. This is a rather surprising result, as in the laboratory session there was a specific assignment to simulate as well




(a) (b)

*Figure 3.3: Fig. 3.3a is James's Bode plot and 3.3b shows John's Bode plot.*

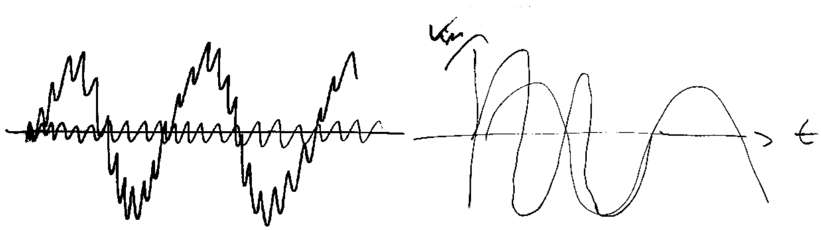
as to measure the phase-characteristic based on a comparison of the input and the output voltage signals.

### 3.4.6 Real-life signal

A last topic we wanted to have a closer look at is the understanding of a real-life signal. Because all students only made drawings of pure sine-shaped input signals, we wanted to probe their understanding of multi-frequency signals. In three of the interviews we asked the students explicitly to sketch a signal with two frequency components. Only James was able to draw a correct signal and to explain how it would look after passing through a high-pass filter. Jack made a sketch of two signals, claiming it was a single signal with two frequencies. Their sketches are in Figure 3.4a and 3.4b respectively. Jeff had "*no idea, to be honest*" about what such a signal would look like. As this is the core use of a filter, we consider this a very important topic. We also asked a more difficult question, namely to construct a band-pass filter. Again, only James came up with the correct solution of simply putting a high-pass and low-pass filter with adjusted cut-off frequencies in series.

## 3.5 Conclusions and future research

Several difficulties students have with basic AC- and DC-circuits seem to persist in more advanced circuits. These include current-based reasoning, difficulty understanding potential, difficulties with phase difference and, more general,




(a) (b)

*Figure 3.4: Fig. 3.4a shows James' (correct) sketch of a signal with 2 frequencies, and the output of a HP filter, while Fig. 3.4b is Jack's sketch of a signal with 2 frequencies.*

a lack of conceptual understanding. Moreover, we also found indications of previously unidentified difficulties. Students don't seem to be able to fully understand what a “signal” physically is, most likely because they have only encountered sinusoidal signals. They also seem to lack a functional understanding of a frequency-based representation of a filter (Bode plot), despite having encountered it multiple times during lectures and laboratory sessions.

Because these interviews have proven to be an effective way of probing students' understanding, we intend to conduct more interviews at different institutions during the next academic year. We hope to get a more complete overview of general student difficulties with basic electronics. In a subsequent step, we will study the learning process during the lab sessions itself.

# Chapter 4

# Student understanding of phase shifts, frequency and Bode plots

**Context**

The interviews discussed in Chapter 3 served to get a broad idea of what problems students had with first order $RC$-filters. However, interviews are not enough to verify how *widespread* those issues are. Additionally, it is hard to *compare* different (semi-structured) interviews consistently to verify how students' understanding evolves after following a laboratory or to compare different laboratories, for example. To gain insight in these aspects, a conceptual questionnaire was developed based on the interviews as well as on findings from literature. This questionnaire was administered to the students before they took the lab on $RC$-filters and approximately one month after that lab session. An example of this test is added in Appendix B. Questions on two topics were included in the test: signals and circuits. The signal questions were prompted by the interviewees' problems with drawing a signal with two frequencies, as well as their issues with phase and Bode plots. This chapter gives a more detailed overview of the questions related to problems with signals, explaining the construction and analysis of the questions as well as the results for the original laboratories. Chapter 5 will cover the questions related to circuits.

The questionnaire was also administered to an adjusted version of the laboratory. The results of that iteration are in Chapter 9.

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## 4.1 Introduction

All engineering programs in Belgium include at least an introductory electronics course, in which basic concepts related to signals are taught. Moreover, most electronics engineering curricula contain a separate course dedicated to signals and systems. The research reported in this article is part of a bigger project on student learning in electronics laboratories. This study focused on student understanding of concepts related to signals.

## 4.2 Literature overview

In physics education research, student ideas on DC circuits have been looked at in detail, but AC circuits and electronics did not get as much attention. Research in the context of (electrical) engineering education however mentions different student problems related to signals.

One issue found is that students often have problems related to phase, also outside electronics, for example when studying sound waves.[108] In the electronics domain, Kautz showed that students have problems with the relative phase of voltages and currents in circuits with reactive elements and with using phasors.[77, 82, 109, 110] Students tend to think there is a phase shift between the voltage across a capacitor and the input voltage of the circuit, instead of between the current through and voltage across a capacitor. Bernhard also found that students have problems adding signals that are not in phase: students "quite consistently neglected phase and did 'pure arithmetic' addition."[79] They had problems relating the mathematical representation of phasors and complex numbers to real-life signals.[67] Maher's students had little trouble understanding that a low-pass filter will cause attenuation depending on the frequency, but struggled with the fact that it also causes a phase shift.[78] Also in developing and administrating the Signals and Systems Concept Inventory (SSCI), it became clear students often omit the phase shift between the output and input signal of systems, despite being given the phase characteristic. [59, 111] In a pilot study for the SSCI, some students mentioned 'phase response' was troublesome, although it was not as troublesome as for example convolution.[86] Scott even states that phase is a so-called threshold concept.[112]

In all studies mentioned above however, phase is discussed in a specific context. Because of this, it is unclear whether the problems students have in those studies are problems about phase shifts themselves or rather about the occurrence of a phase shift in a particular situation.

Since a main application of filters is to alter or select signals as a function of frequency, it is important for students to understand how a signal can be composed of different frequencies. As mentioned before, Bernhard found that students have difficulties adding signals that are not in phase.[67, 79] Similarly, Holton saw that students have “difficulty thinking of circuit behaviour when multiple waveforms, frequencies are combined.”[62] He also found that some students think of an AC-signal as a signal that has a magnitude varying along a wire instead of varying in time, leading to problems when answering questions that require thinking about the circuit in the time-domain.

A third important concept in electronics is a Bode plot. Again, several authors have looked into it, Bernhard calling it a possible threshold concept for electronics engineers.[83, 84] His students had problems both drawing and using Bode plots across various courses. Also in the SSCI, students had trouble constructing Bode plots from a given transfer function.[85] They also had difficulties understanding what happens to a signal when passed through a system, given its Bode plot. The same authors found that students themselves find Bode plots a troublesome concept.[86] The studies all probed students’ ability to construct a Bode plot based on a given a transfer function. Students’ understanding of a Bode plot as a representation of the relation between input- and output-signal as a function of frequency is rarely verified, especially not starting from signals.

The present study adds to prior research by examining students’ ability to graphically represent different concepts related to signals. The following research questions are answered:

1. Are students able to graphically represent a phase shift in the time domain?
2. How do students graphically represent a signal consisting of 2 frequencies in the time domain?
3. Are students able to construct a Bode plot based on experimental data?

## 4.3 Methods

### 4.3.1 Questionnaire

To answer the research questions, an open-ended questionnaire was administered to the students before and after a lab on $RC$-filters. This questionnaire contained three questions related to the graphical representation of signals. The formulation of these questions was inspired by 11 earlier student interviews. [96] These interviews aimed to detect students' conceptual problems with first order $RC$-filters. Various issues surfaced, including several related to how students understand signals. As found in literature, students ignored the phase shift of the output signal [67, 78, 85], had no idea how a signal with two frequencies would look like [62, 67, 79] and struggled with Bode plots. [83–85]

The first question (see Figure 4.1) in the questionnaire showed a sine wave and asked students to draw a signal that was either lagging or leading (depending on the test) the sine by 90°. The reason for asking this question was the omission of a phase shift by the students during the interviews, despite them measuring it explicitly during labs. It allowed verifying whether the problem was due to the concept of a phase shift itself, regardless of the reason why a phase shift occurs in a specific context.

One of the main applications of a filter is the processing of signals with multiple frequencies. Because few of the interviewed students were able to sketch such a signal, the second question (Figure 4.3) asked the students to sketch a signal with two frequencies. The axes were labelled in the time domain to verify students' graphical understanding of a signal in that domain.

During the interviews, students showed many problems dealing with Bode plots, both in constructing them and in using them once they had sketched one. During the labs, they had to construct one from their measurements. The final question (see Figure 4.6) asked to construct a Bode plot from a set of example measurements. This question was meant to verify whether or not students understood a Bode plot as a (graphical) representation of the output-input relation as a function of frequency, without mentioning the transfer function.

### 4.3.2 Participants and Educational Background

All participants to both the interviews and the questionnaire were second year engineering students, spread across three campuses in Belgium. They all followed an introductory course in electronics, consisting of lectures and lab sessions. Typically, the labs focused on a specific topic covered during earlier lectures.

One lab session was about first order passive $RC$-filters. Although the duration of the labs differed, the content was largely the same: students worked in pairs and received a (known) resistor and capacitor, configured as a low- or high-pass filter (LPF or HPF). They applied a specific (AC) voltage using a signal generator and measured the amplitude of the output and its phase shift with respect to the input using an oscilloscope. By calculating the gain and varying the frequency of the input, the students could construct a Bode plot.

The questionnaire was administered at 3 different campuses in the 2012-2013 academic year. 181 students answered the survey before entering the $RC$-filter lab, but after lecture instruction. Approximately 1 month after the lab, 156 students filled in the questionnaire with questions slightly altered (e.g. leading instead of lagging signal). 128 students completed both questionnaires.

### 4.3.3 Analysis

The analysis did not focus on 'correct' or 'incorrect' answers but on gaining a nuanced understanding of what aspects students understand and what aspects are troublesome. Therefore, a set of descriptive categories was derived for each question bottom-up from the students' answers, using a phenomenographical approach.[113] The categories were set up by one author, after which another author categorised a subset of the data independently using these categories scheme. The inter-rater reliability was verified using Cohen's $\kappa$ and is reported for every question.

Since the main aim of this paper is to discuss student issues, the emphasis is on the description of student answers, rather than a statistical analysis of student gain, prevalence of answers or differences across colleges. Since there was little difference between pre- and post-test, numbers or percentages mentioned refer to the entire group of 337 surveys unless specified otherwise.

## 4.4 Results

### 4.4.1 Phase shift

All students answered this question, 70% doing so correctly. Students sketched signals with a phase shift of +90°, -90° and 180°, both when the question asked for a leading as well as for a lagging signal. An overview is in Table 4.1. There was perfect agreement between both raters, resulting in a Cohen's $\kappa$ of 1.

A correct answer meant that both the magnitude and sign of the phase shift were correct. The biggest problem was the *sign* of the phase shift: 299 (90%) of

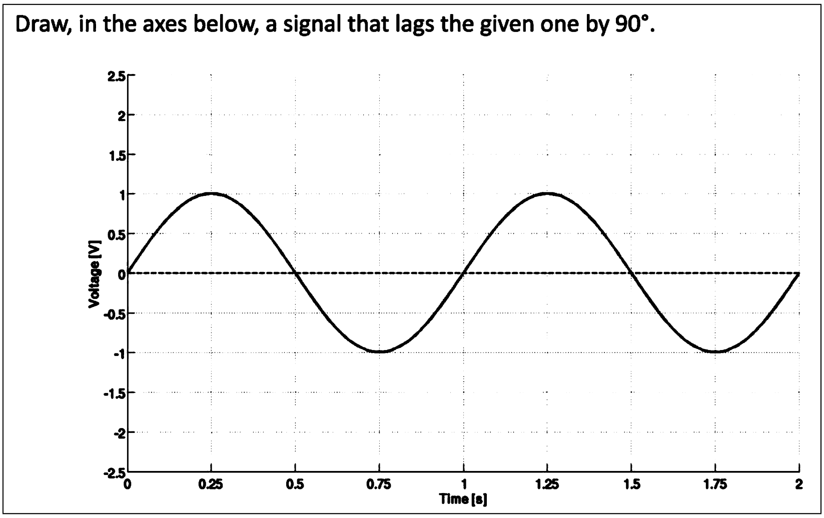



*Figure 4.1: Phase shift question.*

the students sketched a shift of |90°|, but 20% of this group (61 students) did so with a wrong sign. A positive phase shift seems to be easier than a negative one (85% correct vs. 75%) and students seem to perform slightly better after the lab (67% correct vs. 75%), although neither of these differences is significant (at the $\alpha = 0.05$ level for a binomial test).

Some answers (28 or 9% of all answers that showed a |90°| phase shift) looked like the sketch in Fig. 4.2, with a signal starting later/earlier in time rather than at the same time of the given signal. In most of these cases (21, 75%), the signal that was sketched had a negative phase shift, regardless of what was asked in the question. This did not depend on individual students (only one did it in both pre- and post-test), nor did it occur more (or less) in the post-test (15 pre, 13 post). Students who gave a correct answer were less likely to do this (7% vs. 18%).

### 4.4.2 Signal with two frequencies

All correct categories are shown in Fig. 4.4, wrong ones are in Fig. 4.5. Some students used a frequency-domain representation at campus 1 and 2, when the axes provided were not yet labelled by the authors. An overview of the frequency of each category is in Table 4.2. Cohen's $\kappa$ was 0.76, indicating a substantial agreement. [114]

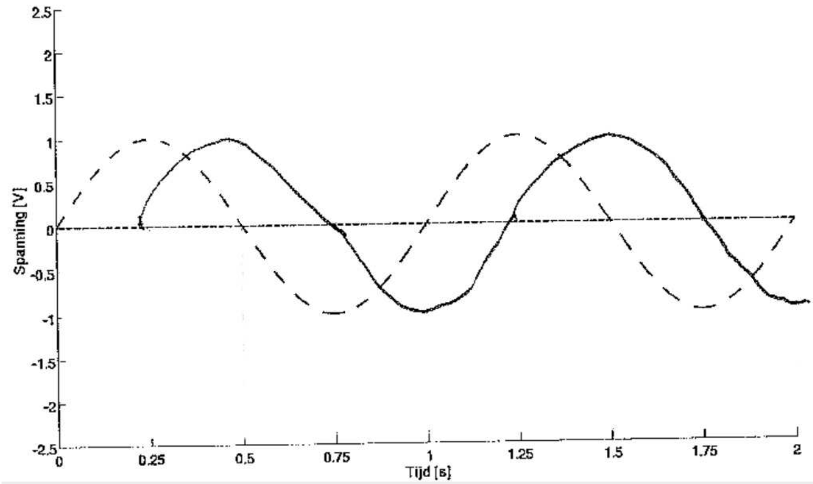



*Figure 4.2: Time shifted signal, starting later than the given signal (dashed). 21 of the 28 cases showed a negative phase shift.*

*Table 4.1: Results of phase shift question. Number and percentage of students per category.*

| Category | Pre | Post | Overall |
|---|---|---|---|
| Correct | 121 (67%) | 117 (75%) | 238 (71%) |
| \|90 °\| | 35 (19%) | 26 (17%) | 61 (18%) |
| 180° | 21 (12%) | 12 (8%) | 33 (10%) |
| Other | 4 (2%) | 1 (1%) | 5 (1%) |
| Blank | 0 (0%) | 0 (0%) | 0 (0%) |

The answers were considered correct when they can be constructed by adding two sines (with a different frequency). Overall, 57% of the students gave a correct answer, 30% gave an incorrect answer while 13% left the question blank. Of the correct answers, the one in Fig. 4.4c was the most popular, although the 'noisy sine' of Fig. 4.4a was also very popular after the lab (21% vs. 8% before). The former indicates that students are not familiar with multiple frequency signals and construct a signal 'manually' by adding two sines with a slightly different frequency almost point by point. Before the lab, 15% of the students left this question blank, while only 7% did so after, which is a significant difference. Most of the students who left the question blank initially, arrive at a correct sketch in the post-test (15 out of 24).

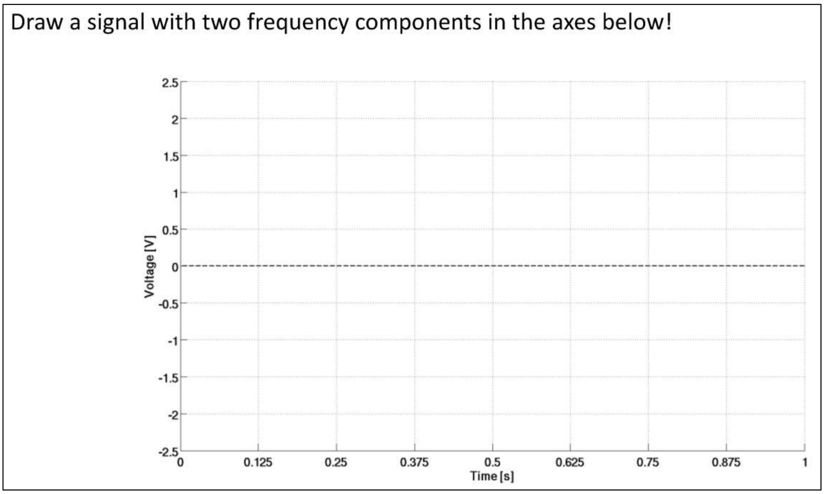



*Figure 4.3: Double frequency signal question.*

Of the incorrect answers, the FM signal is probably used because students encountered it in other courses. The overlapping signals could point to problems understanding either the physical reality (there can be only one potential at a certain point in time) or misunderstanding of a mathematical function. While it is also possible students sketch this because it is similar to what they see on an oscilloscope screen, this is unlikely since there are less students doing this after attending the lab. It is unclear why students sketch a Bode plot here, although this may be triggered by the word 'frequency'.

### 4.4.3 Bode plot

The 'measurements' used in Fig. 4.6 stem from a band-pass filter (BPF), to avoid the students relying on memory and drawing a low- or high-pass filter (LPF or HPF) they studied in lectures and labs. The input amplitudes are different, which is not something they encounter during the lab or lectures. The output amplitudes are chosen to make the calculations easy (powers of 10) or familiar (-3 dB). Finally, the assignment specified that the circuit consists only of passive components. An overview of all student answers is in Table 4.3. Cohen's $\kappa$ was 0.8071, indicating clear agreement.

The analysis focused on the *curves* the students sketched, without taking axes labels or indicated values into account. This means that an answer that is

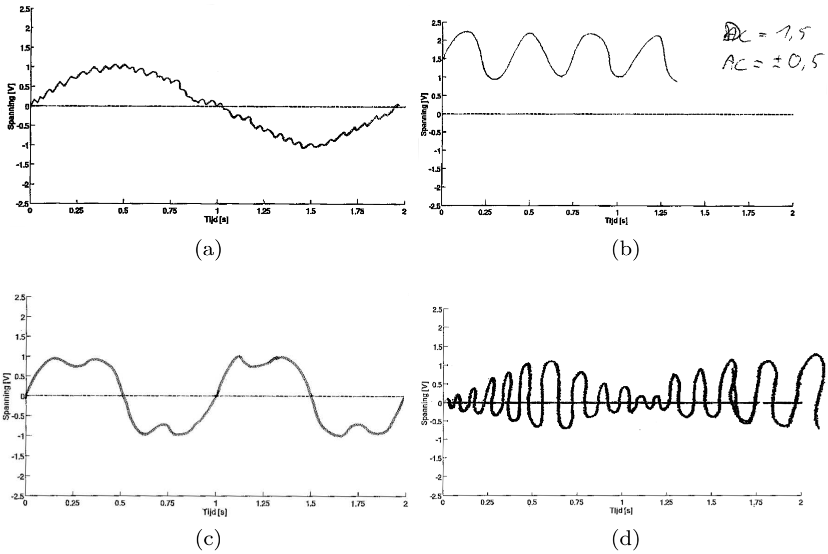



*Figure 4.4: Correct answers of students to the first question, 192 in total (57%), including frequency-domain representations. The Dutch labels on the axis mean "Time [s]" and "Voltage [V]" for the horizontal and vertical axis respectively. 4.4a is a noisy sine wave. 4.4b has a DC-offset, with the student explicitly indicating the DC-offset. 4.4c is a manually added signal. 4.4d is an AM-like signal. An overview of frequencies of the different categories is in Table 4.2.*

categorised as a BPF is not necessarily correct: the pass-band could be >0 dB or the y-axis labelled in V for example. Even when using this criterion, only 12% of students sketched a BPF before the lab. See Fig. 4.7 for an example. This number increased to 23% after the lab.

The incorrect answers (see Fig. 4.8) fall into two groups: those that are Bode plots and those that are not. The former contained 35% of the answers. The majority of these answers showed a Bode plot of an LPF or HPF. This suggests that students rely on memory and sketch a curve they encountered before. This seems confirmed by the slight raise in answers in this category after the lab (from 28% to 33%), where they again use an LPF or HPF. Of this group, most actually showed a graph $> 0$ dB. Before the lab, 50% of those sketching a BPF did this, while the other groups did so in 80% of cases. After the lab, this increased to 90%, both for those sketching a BPF and those sketching different Bode plots. The answers that were not a Bode plot usually showed one or several signals or only labelled axes. 22% left this question blank before the lab, 17% after.

*Table 4.2: Results of double frequency question. Number and percentage of students per category.*

| | Category | Figure | Pre | Post | Overall |
|---|---|---|---|---|---|
| CORRECT | Noise | 4.4a | 15 (8%) | 33 (21%) | 48 (14%) |
| | Offset | 4.4b | 1 (1%) | 2 (1%) | 3 (1%) |
| | f-domain | / | 2 (1%) | 8 (5%) | 10 (3%) |
| | AM | 4.4d | 3 (2%) | 8 (5%) | 11 (3%) |
| | Manual | 4.4c | 63 (35%) | 58 (37%) | 121 (36%) |
| INCORRECT | FM | 4.5b | 16 (9%) | 10 (6%) | 26 (8%) |
| | Sine | 4.5c | 13 (7%) | 4 (3%) | 17 (5%) |
| | Overlap | 4.5a | 17 (9%) | 8 (5%) | 25 (7%) |
| | Bode plot | 4.5d | 9 (5%) | 1 (1%) | 10 (3%) |
| | Other | / | 12 (7%) | 12 (8%) | 24 (7%) |
| | Blank | / | 30 (17%) | 12 (8%) | 42 (12%) |

*Table 4.3: Results of Bode plot question. Number and percentage of students per category.*

| | Category | Fig. | Pre | Post | Overall |
|---|---|---|---|---|---|
| BODE | BPF | 4.7 | 22 (12%) | 36 (23%) | 58 (17%) |
| | BSF | 4.8a | 6 (3%) | 2 (1%) | 8 (2%) |
| | LPF/HPF | 4.8b | 50 (28%) | 51 (33%) | 101 (30%) |
| | Filters | 4.8c | 6 (3%) | 6 (4%) | 12 (4%) |
| NOT BODE | Signal | / | 4 (2%) | 0 (0%) | 4 (1%) |
| | Signals | 4.8d | 3 (2%) | 3 (2%) | 6 (2%) |
| | Points | / | 0 (0%) | 1 (1%) | 1 (0%) |
| | Axes | / | 32 (18%) | 14 (9%) | 46 (14%) |
| | Other | / | 18 (10%) | 17 (11%) | 35 (10%) |
| | Blank | / | 40 (22%) | 26 (17%) | 66 (20%) |

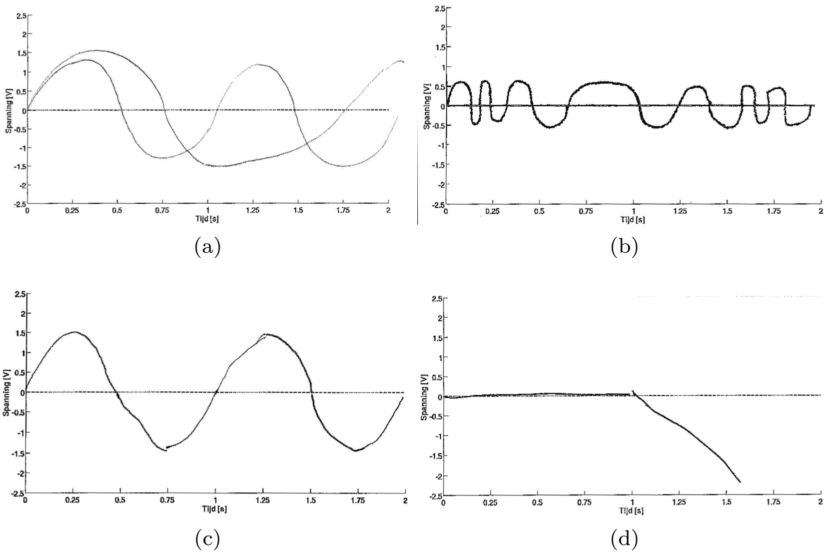



*Figure 4.5: Incorrect answers of students to the first question, 144 surveys (43%), including blanks. The Dutch labels on the axis mean "Time [s]" and "Voltage [V]" for the horizontal and vertical axis respectively. 4.5a are overlapping signals. 4.5b is an FM-like signal. 4.5c is a single-frequency signal. 4.5d is a Bode-plot. The frequency of all categories is in Table 4.2.*

# 4.5 Discussion

## 4.5.1 Phase shift

Several authors found that students have problems with phase in various contexts, as did our students during the interviews: they did not include a phase shift in the output of an $RC$-filter, despite measuring it repeatedly during their labs. [77, 78, 111]

When directly asking students to draw a phase shift, most are fully capable of doing so. All are well aware that a phase shift is a shift in time (and not, for instance, a change in amplitude or offset). The main problem students have is with the *sign*: they often confuse lagging and leading. It appears that the students do not have a real problem with the concept of a phase shift, but rather with understanding it in a given context. This may be because they do not understand its physical interpretation.

An **unknown** circuit consists of only resistors and capacitors. To find out how the circuit behaves, **4 measurements** are done. A different AC-voltage is applied every time. The results are in the table below: the amplitude and frequency of the input signal and the amplitude of the output signal are indicated in the table.

On the axes below, draw a possible **Bode plot** for these measurements.

Don't forget to label the axes!

| Measurement | $V_{in}$ [V] | $f_{in}$ [Hz] | $V_{uit}$ [V] |
|---|---|---|---|
| **1** | 1 | 1 | 0,100 |
| **2** | 1 | 10 | 0,707 |
| **3** | 10 | 1 000 | 7,071 |
| **4** | 10 | 10 000 | 1,000 |

*Figure 4.6: Bode plot question.*

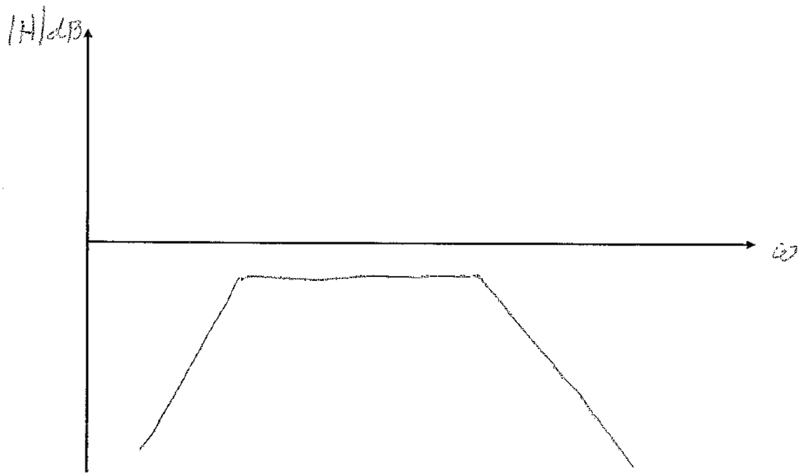
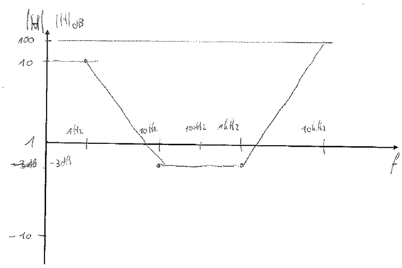



*Figure 4.7: Correct answer to the Bode plot question: a band-pass filter (BPF). Please note that these are not necessarily correct drawings, since they also include for example those with incorrectly labeled axes.*

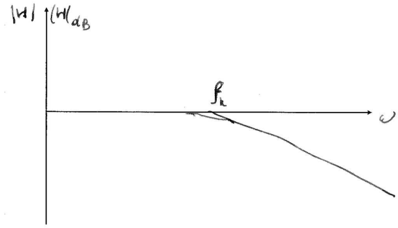
The answer in Fig. 4.2 shows that some students think of a phase shift as a later start in time, rather than a start at a different part of the cycle. It is also possible that they think of a leading signal as one that is leading in space rather than in time, as Holton observed.[57] This would lead to a signal that appears to be lagging. So while students know what a phase shift is on a plot, it is not sure they can interpret or apply it in a certain *context*. The reason for students omitting the phase shift during the interviews is therefore most likely that they do not know (why) a phase shift occurs in the specific context of an $RC$-filter, rather than not knowing what a phase shift is.

### 4.5.2 Signal with two frequencies

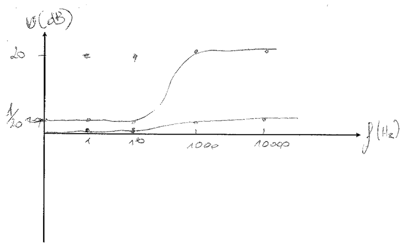
From literature, it is known that students do not have a clear idea how to process signals with multiple frequencies. Here, it became apparent many do not know how to construct those signals in the time domain. Also, most correct answers are like the one in Fig. 4.4c, which stems from manually adding two signals on the spot. Only few students sketched examples that have practical use for a filter.



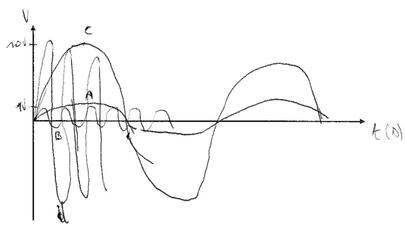

(a)




(b)




(c)




(d)

*Figure 4.8: Wrong answers to the Bode plot question, N=279 (83%), including 66 (20%) blanks. 4.8a is a bandstop filter. 4.8b is a low-pass filter. Some students thought the different input signals would result in different Bode plots, see 4.8c. 4.8d is a collection of various signals. In addition to the examples shown, some students only labeled their axes (not necessarily correctly) and others did still something else or left the question blank altogether. An overview of the frequency of each category is in Table 4.3*

### 4.5.3 Bode plot

The biggest problem students have in our study is with a Bode plot. Bernhard [83] as well as Wage [85] showed that students do not know how to relate a transfer function to a Bode plot. From our study, it becomes clear that students do not grasp the concept of a Bode plot as a representation of the input-output relation as a function of frequency. Despite a lab session in which they explicitly have to construct a Bode plot from a set of measurements, most students do not even manage to draw a sketch that is at least a Bode plot. Those who do manage, usually associate the term 'Bode plot' with that of an LPF or HPF, recalling a shape they encountered in their lectures and labs. In addition, they do not realise that a signal >0dB means there is amplification. All of this shows that rather than having problems converting a transfer function to a Bode plot, they do not understand what a Bode plot is: a representation of the gain as a function of frequency.

## 4.6 Conclusion

From the survey, it seems that the problems students have with signals in the interviews and literature are not due to a bad understanding of the signals themselves: they know what a phase shift is and most students are also able to draw a signal with two frequencies. Most likely, students struggle with the interpretation of signals in a specific context, most notably with the phase.

The problems they have with Bode plots are not limited to their relation to the transfer function of a system, but rather to the overall concept of a Bode plot as a representation of the gain as a function of frequency. They tend to rely heavily on memory when answering this question and do not realise that attenuated signals can never have a gain >0 dB.

Students keep struggling with the issues described above, even (more) after laboratory instruction. In our design of a new laboratory session, we will keep these findings in mind in order to foster student learning of those concepts.

# Chapter 5

# Student understanding of first-order *RC*-filters

**Context**

During the interviews discussed in Chapter 3, the students not only had problems with signals, but also with various topics related to circuits and circuit laws. Therefore, the conceptual test discussed in Chapter 4 also contained two questions related to *RC*-filter circuits. These circuit questions arose from the various problems with circuit laws encountered in the interviews, but also allowed for a verification of the extent to which students identified an *RC*-circuit as a filter correctly. The latter was done because only one of the students who were interviewed was able to sketch the circuit of a filter when asked. This chapter provides a detailed overview of both questions, explaining the construction and analysis of the questions as well as the student answers for the original laboratories. The answers of the students who followed the black box laboratories are discussed in Chapter 9.

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Pieter Coppens, Johan Van den Bossche, and Mieke De Cock. "Student understanding of first order RC -filters". In: *American Journal of Physics* (2016)

## 5.1 Introduction

In engineering education, students generally encounter electrical circuits for the first time in an introductory physics course. They learn how to calculate specific currents and voltages, using Kirchhoff's laws and Ohm's law. The focus in such an introductory course is often on DC circuits with frequency-independent components (ideal batteries, wires and resistors). The first frequency-dependent component students typically encounter is a capacitor. It is introduced in terms of charging and discharging in a circuit with a resistor and capacitor in series, analyzed in the time domain. However, in introductory electronics courses, students learn how to look at circuits from a different point of view. These courses typically start by analyzing the same $RC$ circuit, but now in terms of filtering, input and output voltage and cutoff frequency. The analysis is done in the frequency domain and input signals are AC voltages instead of DC voltages. In this paper, we focus on student understanding of and reasoning about such first order passive $RC$ filters because they are at the transition from DC (about which a lot of research exists) to AC circuits and the transition from time-domain behavior to frequency-domain behavior. As such, they allow the introduction of typical electronics topics via a familiar circuit. When referring to a 'filter' in the remainder of the article, a first order $RC$ filter is meant, unless specified otherwise.

This study is part of a bigger research project about student learning in introductory electronics laboratories. Here, we report on student answers to two questions on a questionnaire related to $RC$ filters. The context and methods are explained in section 5.3, while the questions and their analysis are in sections 5.4 and 5.5. The most important findings are summarized in the conclusion of section 5.6, together with implications for teaching. But before that, we will start with a short literature overview in Section 5.2.

## 5.2 Literature overview

Over the past decades, a lot of research has been done on student understanding of basic electric circuits, we refer to the literature review in Zavala's thesis for an excellent overview.[65] Most of this research focused on so-called 'bulbs and batteries' questions, probing student understanding of current and voltage as well as Kirchhoff's laws and Ohm's law in passive DC circuits. Picciarelli, Di Gennaro, Stella and Conte for example found that students struggle with interpreting Ohm's law: they think that current causes a potential difference instead of the other way around. For instance, some students think that when adding a resistor parallel to an existing one, the total current will increase (correct), which consequently causes the potential difference across the original resistor to increase as well (incorrect).[70] Holton, Verma and Biswas observed problems with Kirchoff's current law (KCL), which are similar to those encountered by Engelhardt and Beichner.[57, 58] Students for example think that at a node, current is always split equally between the different branches, regardless of the impedance of each branch. This is also referred to as so-called local reasoning.

Besides problems with the laws as such, McDermott and Shaffer found that students often reason locally and sequentially instead of holistically about a circuit.[66] This means that they only focus on where a change was made, rather than acknowledge that that change may influence the circuit at a different point. In other words, they fail to *combine* the different laws that govern a circuits' behavior. An example is when students are asked what happens to the brightness of a bulb in series with two others in parallel when one of the parallel bulbs is removed. They often think there will not be any change. Various other studies also observed these misconceptions with their students.[62, 84]

Cohen, Eylon and Ganiel found that students tend to reason based on current instead of voltage or potential, which is the underlying reason for students' sequential reasoning.[66, 68] A consequence is that some students have problems with an open switch: they think there cannot be a potential difference across an open switch, since "there is no current, hence no voltage" [1]. This student applies Ohm's law instead of using Kirchhoff's voltage law (KVL). This type of reasoning will be referred to as 'current-based reasoning' (CBR) in the rest of the paper.

Although most of the research mentioned concerns resistive circuits, there have also been some studies on student understanding of capacitive circuits, mainly on charging and discharging capacitors in a DC situation.[57, 62, 75, 76]

When switching from DC to AC, many of the issues found for DC circuits remain, but also new mathematical and conceptual difficulties arise. Students sometimes ignore or misinterpret KVL. [77] Others think the voltage varies spatially along a wire instead of in time. [57] A final, but important, problem students have is that they do not appreciate the frequency-dependency of the circuit and have difficulties with phase behavior.[62] A problem students have with phase shifts is that because of them, one cannot simply add amplitudes (or RMS values) algebraically.[67, 79, 116] Another issue is that they sometimes do not realize there is a phase shift between current through and voltage across the same component, but think there is one between "either quantity relative

[1] Quote from a student answer in the authors' study

to some other current or voltage in the circuit."[77]

The research on student understanding of *RC* circuits with AC input signals is so far limited and usually focused on the phase shift between current and voltage.[77] One question of the AC/DC Concept Inventory asks about a high-pass *RC* filter (HPF), where students often mistake it for a low-pass filter (LPF) or do not appreciate the frequency dependent behavior of the circuit at all.[57]

When studying circuits in the frequency domain, Bode plots are an important tool. These plots show the gain of the circuit (output voltage over input voltage) in decibel (dB) as well as the phase shift of the output signal with respect to the input signal as a function of frequency. The frequency axis is shown on a logarithmic scale to allow for a wider frequency range. An example of the gain portion of the Bode plot of a high-pass filter is in Fig. 5.4. Bode plots are widely used in electronics and system theory to visualize the behavior of a filter or amplifier. In this paper, only the gain plot is discussed and any mention of 'Bode plot' in the remainder refers to the gain plot unless indicated otherwise. There has been some research in this field, mostly from a system-theory point of view.[83, 111, 117] The focus of this earlier research is on the mathematical aspects of transfer functions (e.g. its poles and zeros) in relation to the shape of the Bode plot itself (e.g., a 20dB decrease and increase in the slope, respectively), regardless of a specific context.

## 5.3 Context and methods

With the exception of one question in the AC/DC Concept Inventory, none of the studies mentioned in section 5.2 look at circuits in terms of filters. Most focus on DC voltages and currents, usually in steady state or in the time domain, and describe student problems with basic circuit laws (Ohm's and Kirchhoff's laws for example). In electronics courses however, circuits are discussed from a 'filter' point of view, namely as systems having an input and output voltage. The analysis (and construction) of circuits focuses on the relationship between input and output and is almost always done in the frequency domain, using tools such as Bode plots. In Belgium, a typical engineering curriculum has a physics course in the first year, in which *RC* circuits are introduced via charging and discharging a capacitor with a DC voltage. In the second year, these circuits are the topic of the first lectures (and labs) of an introductory electronics course, now from a 'filter' point of view: the inputs are now *AC* signals and the frequency-dependent behavior of the circuit is studied.

In this paper, we aim to verify whether or not engineering students studying electronics recognize an $RC$ circuit as a filter. In addition, we want to study how well they understand or apply basic circuit laws and to what extent problems with DC circuits discussed in literature carry over to AC circuits. Therefore, the focus of this paper is on two aspects of student understanding of passive first order $RC$ filters that have not been studied before and we will answer the following research questions:

- How do students understand the influence of an AC versus DC input signal on the magnitude of the output signal for a given passive first order low-pass $RC$ filter (LPF)?
- How do students understand the influence of the components (resistor and capacitor) of a passive first order high-pass $RC$ filter (HPF) on the magnitude of the output signal for a given input signal?

### 5.3.1 Questionnaire

To answer both research questions, an open-ended questionnaire was developed, in which two questions related to first order $RC$ filters were included. Three more questions were related to signals and are discussed in a separate paper.[107] The formulation of these questions was inspired by findings from 11 interviews in the spring semesters of 2011 and 2012 with second year engineering students who followed an introductory electronics course and who completed a laboratory on $RC$-filters a month prior to the interview.[96] These interviews aimed to detect students' conceptual problems with first order $RC$ filters, if any. Various ideas and misconceptions surfaced, including several encountered in literature. The main problems encountered were the following:

- Problems with potential difference, e.g. measuring input and output voltage across the same capacitor as the interviewed student in Fig. 5.1 did;
- Current-based reasoning [when discussing an LPF with a DC input] *"That's an open switch, so there is no current flowing through the circuit and then there is no voltage across [the output] anymore."* ;
- Failure to sketch the circuit of a filter and/or uncertainty about the type of filter sketched;
- Problems using a Bode plot: students could only sketch the Bode plot corresponding to circuits they had seen during the lecture but failed to draw a qualitative sketch of e.g. a 'filter that attenuates low frequency signals instead of high frequency ones';

- Problems relating the input signal to the output signal, e.g. omitting the phase shift between both or changing the shape of a simple sine wave;
- Failure to assess the effect of changing a component in the circuit.

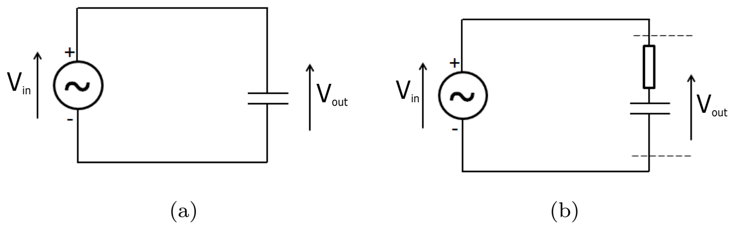


*Figure 5.1: An example of an interviewed student not understanding potential difference. When asked to sketch 'a filter', the student sketched the circuit of Fig. 5.1a, but did not realize that the input and output voltages would be equal, nor that the filter needs a resistor. When probed and encouraged by the interviewer, he added a resistor to his circuit as shown in Fig. 5.1b. When asked to clarify where he would measure the output voltage now, he added the two dashed lines in the same figure, clearly indicating he did not realize that the input and output voltage of his circuit would always be equal. [96]*

To verify to what extent the problems found during the interviews were also prevalent more generally, a survey was developed and administered to a group of second year engineering technology students. The questions are in Sections 5.4.1 and 5.5.1. To force the students to think conceptually rather than fill in a formula, the questions contrasted several qualitative situations and asked students to compare the output voltage of the different situations. Since the main interest was in the approach students used and the extent to which each approach was successful, the questions explicitly asked for an explanation of the given answer. Both questions can be answered by either using circuit laws or by recognizing the circuit as a filter and building a reasoning from there. This approach made it possible to verify which approach is more popular as well as which is more successful. Additionally, the specific nature of the mistakes can be documented.

The first question showed three identical low-pass filters (LPF) with different input signals: 1V DC, 10V DC, and 1V AC. The students were asked to rank the circuits according to the output voltage. The full question is in section 5.4.1, with a discussion of the answer in 5.4.2. As opposed to keeping the circuit constant and changing the input signal, the second question showed four circuits configured as high-pass filters (HPF), each with the same (AC) input signal.

The first filter had component 'values' $R$ and $C$, where the next ones had one or both components doubled or halved, depending on the questionnaire. The exact question is in section 5.5.1, while the answer is discussed in section 5.5.2. Although all questions are printed in English, they were originally asked in Dutch and the students also answered them in Dutch.

### 5.3.2 Participants and educational context

All participants in both the interviews and the questionnaire were second year engineering technology students, spread across three campuses in Belgium. In the first year, they attended an introductory physics course that included an introduction to electricity and circuit laws. This paper is about their introductory course in electronics, consisting of traditional lectures and lab sessions, both taught in Dutch. At one campus, this course was taught as part of the general engineering curriculum in the first semester of the second (bachelor) year, while at both other campuses, it was taught in the second semester of the second year to the students who chose to major in electronics engineering. Typically, the labs focused on a specific topic covered during one or more earlier lectures. One of those lab sessions was about first order passive $RC$ filters. The (Dutch) questionnaire was administered in the 2012-2013 academic year, once just before entering the lab and a second time approximately 1 month after the lab. Since there was no significant change of the answers between the pre- and post-lab results (not in the number of correct answers, verified using a binomial test, nor in the distribution of explanations or answers, verified using a $\chi^2$ test, neither even at the $p = 0.05$ level), the remainder of the article is about the post-lab results only. Similarly, there were no significant differences between the different campuses, so the results presented here are valid for all three campuses. 156 students filled in the questionnaire after the laboratory. Neither the pre-test nor the post-test was mandatory or counted for any credit, but there were no students who chose not to participate at any of the campuses.

### 5.3.3 Analysis

Student answers were analyzed in two ways: the first focused on the *ranking* the students provided so as to determine whether or not there was any pattern there. Then, the *explanations* of the students were categorized, in order to gain a nuanced understanding of what aspects students understand reasonably well and what aspects are problematic to them. Our interest is in reasoning patterns the students use, not only in the classification of answers in terms of right and wrong. The exact categories and their origin are described in sections 5.4.3 and

5.5.3 for the low-pass and high-pass filter question respectively. To establish the validity of the classification of the answers, the third author analyzed a random subset of the data ($N = 37$, 23%) and Cohen's $\kappa$ was used to determine the inter-rater reliability. The result is reported for both questions.

# 5.4 Role of input signal for a low-pass filter

## 5.4.1 Question

Below [see Fig. 5.2] are **3 identical circuits**. A **different input signal** is applied to each one. After some time, the output signal is measured. Sort the circuits according to the **maximum of the output voltage** from largest to smallest. Indicate explicitly if the output voltage is zero or if two output voltages are equal. **Explain your answer!** [Emphasis in the original]

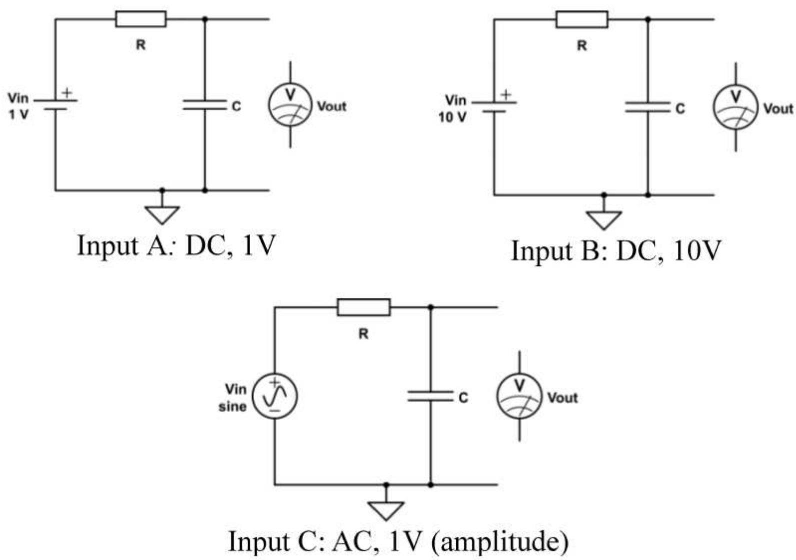


*Figure 5.2: Circuits low-pass filter question*

## 5.4.2 Correct answer

The correct answer is that B>A>C. This can be found in several ways. The first is to recognize the circuit as a low-pass filter, which will allow DC signals to pass undisturbed, but which will attenuate AC signals. A second approach is to use a voltage divider (or circuit laws in general) by replacing the capacitor with its impedance ($Z_C = \frac{1}{j\omega C}$). Using a voltage divider results in $v_{out} = v_{in}\frac{Z_C}{R+Z_C}$. Replacing the (angular) frequency in the formula for $Z_C$ by zero for the DC signal will lead to a correct answer where the DC output signal is equal to the input signal. For AC, the output will be lower, regardless of the specific values of all the parameters. A last, related approach is to replace the capacitor by a short for AC signals (equivalent to an infinitely high frequency) and by an open circuit for DC signals. Although this is not an exact solution (the frequency will be finite in any practical application), this approach is a useful way to quickly gain a qualitative picture of the situation. If Kirchhoff's voltage law (KVL) is applied correctly after replacing the capacitor with a short in AC and an open switch for DC, one finds that the output voltage will be equal to the input voltage for DC signals while for AC it will be zero.

### 5.4.3 Analysis

As mentioned before, the student answers were categorized in two different ways: the first focused on the *ranking* of the circuits and the other on the *explanation* given. The former resulted in 5 specific rankings that accounted for over 80% of all student answers, with the others either giving a different answer or leaving the question blank. These 5 rankings as well as the explanations used by the students are shown in Table 5.1.

The categorization of the explanations the students gave was not done based on a predefined set of categories. Instead, the categories were built bottom-up from the students' answers. The first author went through a first set of answers, marking potential categories using paper and pencil. After going through this first 'training' set using this approach, the most common categories were written down. Then, the answers of a second 'validation' set were assigned to these categories. There were not many answers that did not fit in any of the original categories, therefore all data were analyzed using these categories. A final validation of the categories was done by another author categorizing a random subset of answers independently using the same set of categories. The inter-rater reliability was verified using Cohen's $\kappa$, which was 0.8809, indicating near perfect agreement [114]. The categories were the following:

- *Filter*: The student recognizes the circuit as a filter and builds his/her reasoning from there.
  One student gave the following (correct) answer: "*Is an LPF (low-pass) and so DC will pass easier and 10V DC > 1V DC and so as last C, 1V.*" However, some students do recognize the circuit as a filter, but think it is an HPF: "*A and B are high-pass so do not allow direct current to pass. C is also high-pass so will allow alternating current to pass.*"
- *Open circuit/short*: The student replaces the capacitor by a short for input C (AC) and by an open circuit for inputs A and B (DC). By (implicitly) applying KVL, the student arrives at a correct answer. While it is possible

to arrive at an incorrect answer by replacing the capacitor by a short for DC signals and an open circuit for AC signals, none of the students in our study made this mistake.
An example of a typical answer is the following: "*B,A: capacitor on DC = open circuit ⇒ source voltage across the resistor is across* $V_{out}$. *C:* $V_{out,V} = 0$ *because on AC a capacitor is a short, across which there is no voltage.*"

- *Current-based reasoning (CBR)*: Here the student uses the same approach as before, replacing the capacitor by an open circuit in DC. He correctly states there is no current, from which, however, he concludes there is no voltage either. There is often no mentioning of the AC situation. This results in the incorrect answer $C > A = B (= 0)$. A typical answer was: "*In DC → no current through capacitor; 1V and 10V DC →* $V_{out} = 0V$*;* $C > A = B$."

- *Voltage divider*: Some students (implicitly) use the formula for a voltage divider ($V_o = \frac{Z_c}{Z_r + Z_c} V_i$) and replace the capacitor by the formula for its impedance ($Z_c = \frac{1}{j\omega C}$).
An example of the (implicit) use of a voltage divider was the following: "*[A and B] Low f so C has voltage of the source. [C] large f so voltage divides → so less than 1V!*"

- *AC=DC*: The student does not distinguish between AC and DC input signals and ignores the circuit, resulting in an incorrect answer.
One typical answer was: "$B > A = C$ *input voltage in B is bigger, so output voltage also bigger.*"
Another student wrote the following explanation: "$B > A = C$ *→ DC output voltage of A and C are equal, they are only influenced by the resistor and not by C.*"

- *RMS*: In this answer, the student ignores the circuit but does make a distinction between the AC and DC input signals by looking at the RMS-value of the signals. This most often results in a correct answer. This category also includes students who say that "*average of the AC signal is zero*," that "*the DC signal does not have an amplitude*" or similar incorrect answers that ignore the circuit but focus on the difference between an AC and DC signal.
One example is the student who wrote: "*Source of 1V AC can be replaced by a DC source of* $\frac{1}{\sqrt{2}} V$"

- *Other*: Any other explanations included by the students.

- *No explanation*: This category contains students who did give a ranking of the different circuits, but did not include an explanation with it.

- *Blank*: The students who did not provide any answer and left the question blank.

### 5.4.4 Results

*Table 5.1: Results of low-pass filter question with varying input signal. Number of students who give a certain answer and give a certain explanation with that answer.*

| | **B>A>C**[a] | **C>A=B** | **B>A=C** | **C>B>A** | **B>C>A** | **Other** | **Blank** | **Total** | **Total %** |
|---|---|---|---|---|---|---|---|---|---|
| **Filter**[b] | 10 | 1 | 0 | 1 | 0 | 1 | 0 | **13** | **8** |
| **Open circuit/Short**[b] | 8 | 0 | 0 | 0 | 0 | 0 | 0 | **8** | **5** |
| **Voltage divider**[b] | 6 | 0 | 0 | 0 | 0 | 0 | 0 | **6** | **4** |
| **CBR** | 0 | 4 | 0 | 0 | 0 | 1 | 0 | **5** | **3** |
| **AC=DC** | 2 | 0 | 8 | 0 | 0 | 1 | 0 | **11** | **7** |
| **RMS** | 5 | 0 | 0 | 0 | 2 | 0 | 0 | **7** | **4** |
| **Other** | 8 | 0 | 1 | 0 | 2 | 0 | 0 | **11** | **7** |
| **No explanation** | 39 | 8 | 6 | 5 | 13 | 15 | 0 | **86** | **55** |
| **Blank** | 0 | 0 | 0 | 0 | 0 | 0 | 9 | **9** | **6** |
| **Total** | **78** | **13** | **15** | **6** | **17** | **18** | **9** | **156** | |
| **Total %** | **48** | **8** | **10** | **4** | **11** | **13** | **6** | | |

[a] Correct answer
[b] Correct explanation if applied correctly

The results in Table 5.1 show the number of students for each combination of ranking and explanation, as well as the totals for each categorization (by ranking and explanation). There is a big group of students who give a ranking but do not provide any explanation (over 50%). However, there is no significant difference in the distribution of rankings given by students who include an explanation and those who do not according to a $\chi^2$-test (even at the $\alpha = 0.05$ level). Therefore, it is reasonable to suppose that the explanation underlying the answer of a student who did not provide an explanation is similar to the reasoning of those who do.

The results in Table 5.1 indicate that around 50% of the students gave a correct answer to this question. However, of the 39 students who also explained their (correct) answer, 12 students (over 30%) gave an *incorrect* explanation, such as the RMS-based reasoning and various explanations categorized as 'Other'. If we assume that also 30% of the 39 students who gave a correct answer without writing down an explanation arrived at it using a wrong approach, only one third of all students (not counting blanks) actually arrived at a correct answer by using a correct approach. These students who do give a correct explanation, use different methods, including recognizing the LPF, replacing the capacitor by a short or open circuit in AC and DC situations respectively and using a voltage divider. It is not clear what kind of reasoning the students who gave no explanation used, although the distribution is most likely similar to that of those who did include one.

When studying the distribution of the other, incorrect, rankings, two have a clear correlation with a specific explanation. The first is the ranking $C > A = B$: all but one student who provided an explanation with this answer used current-based reasoning. It is therefore fair to say that the students who used this ranking but did not provide an explanation probably made the same mistake. The second category are the students who do not distinguish between AC and DC input voltages, arriving at the conclusion that $B > A = C$. All students who arrived at this ranking and provided an explanation, fit in this category. Again, the students who arrived at the same conclusion without explaining it, probably made the same mistake.

A final conclusion has to do with both types of (correct) answer categories: using a filter-based approach or using an approach based on circuit theory (e.g. open circuit/short or voltage divider, but also current-based reasoning). The former approach is less popular: 13 students (21% of those who provide an explanation) use it as opposed to 37 (61%). However, the former approach is more successful with a success rate of nearly 80% (10 students) compared to one of barely 50% for the latter.

# 5.5 Component variation for a high-pass filter

## 5.5.1 Question itself

The circuits below [see Fig. 5.3] all have the **same AC voltage** (finite amplitude and finite frequency) as input signal. However, the **values of the resistor and capacitor are different** in every circuit. Sort the circuits according to decreasing **amplitude of the output voltage** (highest to lowest). Explicitly indicate if the output voltage is zero or if the output voltage in two situations is equal. **Explain your answer!**
[Emphasis in the original]

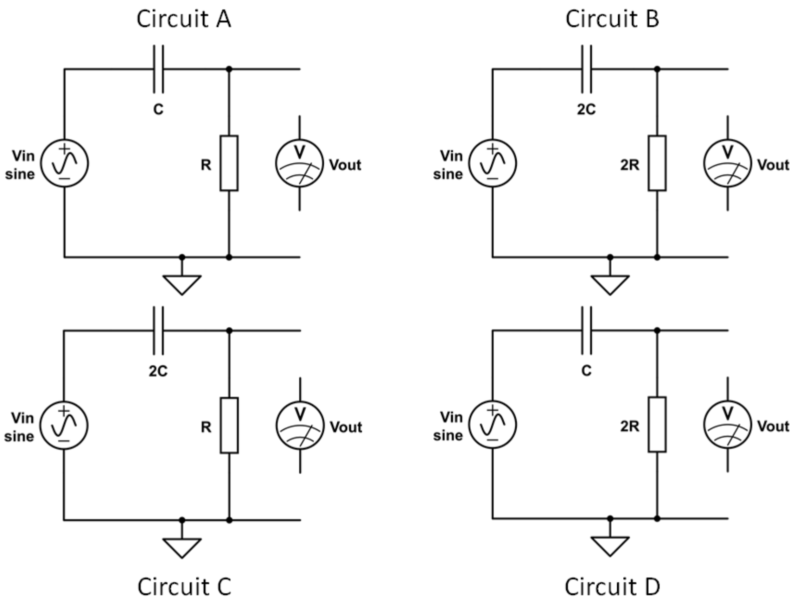


*Figure 5.3: Circuits high-pass filter question*

## 5.5.2 Correct answer

The correct answer is that $B > C = D > A$. This answer can be obtained in various ways, the first of which uses the fact that this circuit is a high-pass filter (HPF). As shown in Fig. 5.4, this can be most easily seen by using the Bode plot of a first order high-pass *RC* filter. When looking at circuits A and

D for example, one can deduce that the cut-off frequency of circuit D will be half that of circuit A ($f_c = \frac{1}{2\pi RC}$). Consequently, the Bode plot of circuit D will 'shift to the left' with respect to that of circuit A, which in turn leads to a higher gain at a certain frequency $f$ for circuit D. This higher gain means that for a constant input amplitude, the output amplitude of circuit D will also be higher than that of circuit A. Using the same approach for all 4 circuits, the Bode plots for circuits C and D coincide, while B will be shifted even more to the left.

A second approach is that there is no current in the DC circuits, so there is no voltage drop across the resistor, resulting in the entire input voltage being across the output terminals (across the capacitor). However, there is a current in the AC circuit, so there is a voltage drop across the resistor, resulting in a lower voltage across the capacitor. Not only that, but doubling the resistor has the same effect as doubling the capacitor. This again leads to the conclusion that circuit B will have the highest output voltage (doubling both the resistor and the capacitor results in an even higher output voltage), followed by circuit C and D and finally circuit A with the lowest output voltage.

It is also possible to explicitly use classical circuit laws (Kirchhoff's laws and Ohm's law) in order to arrive at the same conclusion. The voltage divider approach discussed earlier is essentially a shortcut of this approach.

### 5.5.3 Analysis

As with the low-pass filter question, the answers to this question were also categorized based on both the ranking the students gave and their explanation for that ranking. However, since there are too many possible rankings of 4 circuits (75 when assuming they are ranked from highest to lowest and equality is possible), the answers themselves were analyzed by looking at the relationship between specific *pairs* of circuits shown in Fig. 5.3. The reason for this is that there were too many different rankings used by the students that were all relatively rare. For example, there were only 8 students (5%) who gave the correct answer. Therefore, it is interesting and very useful to have a look at what aspect the other students *did* understand, even though they did not manage to give a fully correct answer. In other words: to find out what the wide variety of other answers have in common. The first aspect is the effect of changing the resistor on the output voltage, done by comparing the 'standard' circuit A to circuit D, in which the resistor is changed. The second is the effect of changing the capacitor, similarly done by comparing circuits A and C. The third comparison was the effect of changing both the capacitor and resistor

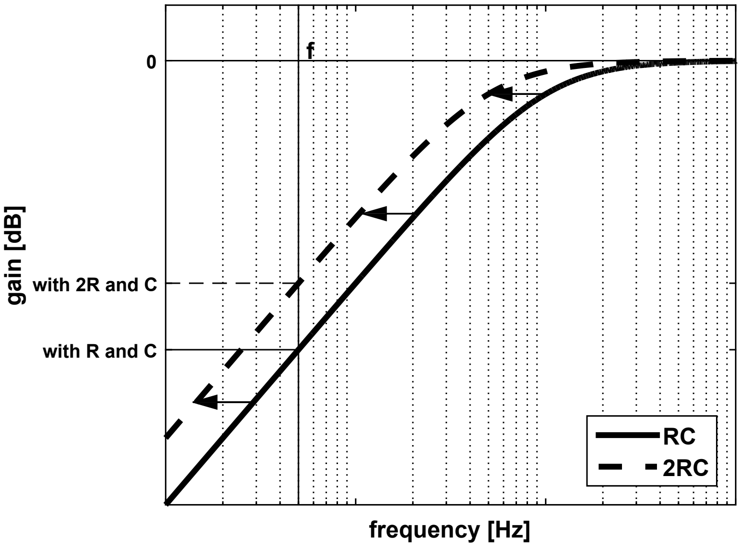


*Figure 5.4: Explanation of high-pass filter question. The solid line represents the gain portion of the Bode plot of a circuit with a resistor with resistance R and a capacitor with capacitance C, configured as a high-pass filter. Doubling the resistor (or capacitor) will result in a curve that is shifted to the left (dashed line), with respect to the original one. At a certain frequency f, the gain (so also the output voltage for an equal input voltage) will then be higher for the circuit with the increased resistor.*

(circuit B compared to A), while the fourth and last one compares the effect of only changing the resistor (circuit D) to that of only changing the capacitor (C). For each of those pairs, there are 4 possible answers: is greater than, is smaller than, is equal to and no information. The latter usually indicates a blank answer, but can also mean that there was an answer given, but without information about a certain pair, for example answering “B>A,” which does not contain any information about circuits C or D.

To explain their answers, students used various strategies. The different explanations are listed below. Again, these categories were found bottom-up from the data, using the same approach used for the low-pass filter question. The Cohen’s $\kappa$ for the eventual categories used was 0.75, still indicating a substantial agreement between both raters [114].

- *Filter*: By recognizing the circuits as high-pass filters and using their cut-off frequency ($f_c = \frac{1}{2\pi RC}$), one can deduce that the higher $R$ and/or $C$, the higher the output voltage will be for a given frequency of the input signal. An example of a correct answer using this approach is the student who wrote that "*HPF:* $\omega_c = \frac{1}{RC}$*,* $R >>$ *[increases, so]* $\omega_c$ *small;* $C >>$ *[increases, so]* $\omega_c$ *small*" while adding a sketch of the Bode plot of a high-pass filter.

However, this approach also went wrong when students think that, for example, the output is proportional to the cut-off frequency or make a mistake in the formula for the cut-off frequency. An example of the former is this answer: "*high-pass filter,* $A = \frac{1}{\sqrt{\omega_c}} \rightarrow$ *if* C *is smaller* $\rightarrow \omega$ *bigger* $\rightarrow f$ *is bigger* $\rightarrow$ *more passes and* $A$ *bigger.*"

- *Voltage divider*: Using the formula for a voltage divider ($v_{out} = \frac{Z_R}{Z_C+Z_R} v_{in}$) the correct answer follows readily by using the impedance of the capacitor, which is inversely proportional to its capacitance ($Z_c = \frac{1}{j\omega C}$). Some students however, made a mistake using this approach by thinking that the capacitor impedance is proportional to its capacitance.

  One student wrote down the exact formula and arrived at the correct conclusion: "$V_o = V_i \left( \frac{R}{R+\frac{1}{j\omega C}} \right)$ *so if* $RC$ *small,* $V_o$ *small.* $C$ *and* $D$ *are equal.* $B > C = D > A$."

  Another one made a mistake by using the capacitance instead of impedance: he wrote $V_o = V_i \left( \frac{R}{R+C} \right)$ for every circuit and (consistent with the formula) arrived at the conclusion that $D > A = B > C$.

- *Circuit laws*: It is possible to use classic circuit laws such as Ohm's law and Kirchhoff's laws to arrive at a correct answer without using the 'shortcut' of a voltage divider. Some students attempted this approach, but none were successful.

  An example of such an attempt is by a student who used (only) Ohm's law: "$X_C = \frac{1}{2\pi C}$*;* $C > A = B > D$*. If you double C, the impedance changes, it becomes twice as small. If you double R, the impedance becomes twice as big.* $R = \frac{U}{I} \rightarrow U = R \cdot I$."

- *R matters more*: Some students think that only the resistance of the resistor matters, or that it matters more than that of the capacitor. The reasoning for this varies, but the following three explanations are typical:

  - The first is related to so-called local reasoning, saying that the output voltage only depends on the resistor simply because it is closer to where the output voltage is measured. What happens 'far away' from there is ignored.

    An example is the following answer: "$B = D, C = A$ *because of Ohm's law. More voltage across resistor and capacitor in AC is* *short.*" Note that this student also did not realize that replacing the capacitor by a short would lead to an equal input and output.

- A second type were those who ignored the capacitor because it would not influence the amplitude: "$A = C > D = B$ *capacitor does not influence the amplitude of the output voltage.*"
  One student further explained that "*The capacitor causes a phase shift, resistor regulates* $V_{out}$*. So R big* $\rightarrow$ *V big.*"
- A last explanation was that the resistor and capacitor both have an influence, but that the capacitance of the capacitor mattered less:
  One student called circuits with a higher capacitor 'better filters': "*Bigger output impedance for [circuits] B and D for AC* $\rightarrow$ *bigger* $V_{out}$*. Better filter* $\rightarrow$ *bigger* $V_{out}$*. A: HPF, B: double HPF, C: double HPF, D: HPF* $\rightarrow B > D > C > A$*.*"
  Another one had a different reason: "*Circuit B has the biggest amplitude. This is because both C and R are doubled. Then comes circuit D because R has more influence than C (is a very small number). Then circuit C and then A.*" This student argued that the total impedance of the circuit is what matters and also made the mistake of thinking that the capacitor impedance is proportional to its capacitance.

- *C matters more*: As with the previous explanation, this means that a student thinks only the capacitor matters or that it matters more than the resistor. There was no clear reason why students did this as their explanations varied greatly.
  Some just wrote that only the capacitor mattered: "$B = D, A = C$ *resistor has no influence on the amplitude, capacitor does.*"
  Others seemed to think via the current, but ignored that the resistor would also have an influence on the current. One wrote: "*the bigger C, the bigger i through C, the less current through R and the smaller* $v_{out}$*.* $D > A > B > C$*.*" This is an example of a misconception about current being 'used up' in 'earlier' circuit elements, leaving less current available for the one where measurements take place, combined with local reasoning.
  One student replaced the capacitor by a short, but also considered the capacitor charging and discharging: "$B = C - D = A$ *Because first the capacitor is a short and all of the voltage will be across the resistor. Then when it discharges, there is again the full voltage across the resistor. Because of this, the resistor does not matter, only the capacitor.*"
- *Other*: Any other explanations included by the students.
- *No explanation*: This category contains students who did give a ranking of the different circuits, but did not include an explanation with it.

- *Blank*: The students who did not provide any answer and left the question blank.

### 5.5.4 Results

The results are in Tables 5.2 and 5.3. The first shows the number of students for each combination of ranking and explanation, as well as the totals for each categorization (by ranking and explanation). The second shows a cross table of all possible combinations of the different rankings of the students who gave a full answer (132 or 85%). There are some interesting conclusions that can be drawn from these tables, which are explained in more detail below:

- Most students know that changing the capacitor and/or the resistor will *influence* the output voltage;
- Many students do not know the *direction* of this influence;
- Many students do not know that the effect of doubling the resistor and capacitor is equal in *magnitude*.

Before delving deeper into the reasons behind the conclusions stated above, it may be interesting to clarify some of the more obvious results from Table 5.2. The first is the low number of students who rank different pairs correctly, ranging from 43% when comparing circuits A and D to only 12% for the comparison of C and D. A second is the low number of students who provide an explanation: 37%. A reason for this could be that it is cognitively hard to rank 4 different circuits in which two parameters are changed simultaneously (as mentioned, there are 75 possible ways to rank the circuits from highest to lowest when allowing for equality between circuits). However, as with the LPF-question, there is no significant difference in the distribution of the rankings given by students who give an explanation and those who do not according to a $\chi^2$-test (even at the $\alpha = 0.05$ level). Given this lack of difference between students who explained their answers and those who did not, it is reasonable to suppose that the reasons underlying the answers of the students who did not provide an explanation are similar to the reasons of those who did.

When looking at the incorrect answers, it is clear that students know very well that changing either the capacitor or the resistor *will have an influence* on the output voltage. There are hardly any students who indicate that changing the resistor or capacitor from the 'standard' circuit A will not have any influence: 1 (<1%) saying that C=A and 6 (<5%) that D=A, respectively. However, most students do not know in what *direction* this influence will be: there are nearly

*Table 5.2: Results of high-pass filter question with varying component values. Number of students who give a certain ranking and give a certain explanation with that answer.*

| | ***RC*-2*RC*** | | | | ***RC*-*R*2*C*** | | | | ***RC*-2*R*2*C*** | | | | **2*RC*-*R*2*C*** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **D>A**[a] | **D=A** | **D<A** | **No info** | **C>A**[a] | **C=A** | **C<A** | **No info** | **B>A**[a] | **B=A** | **B<A** | **No info** | **C=D**[a] | **D>C** | **C>D** | **No info** | **Total** | **Total %** |
| **Filter**[b] | 4 | 0 | 5 | 0 | 5 | 0 | 4 | 0 | 6 | 0 | 3 | 0 | 3 | 4 | 2 | 0 | **9** | **6** |
| **Voltage divider**[b] | 9 | 0 | 5 | 0 | 7 | 0 | 7 | 0 | 3 | 6 | 5 | 0 | 4 | 6 | 4 | 0 | **14** | **9** |
| **Circuit laws**[b] | 0 | 0 | 3 | 1 | 1 | 0 | 2 | 1 | 1 | 2 | 1 | 0 | 0 | 1 | 2 | 1 | **4** | **3** |
| ***R* matters more** | 5 | 0 | 3 | 0 | 3 | 3 | 2 | 0 | 5 | 0 | 3 | 0 | 0 | 5 | 3 | 0 | **8** | **5** |
| ***C* matters more** | 2 | 1 | 2 | 1 | 4 | 1 | 1 | 0 | 4 | 0 | 2 | 0 | 0 | 1 | 5 | 0 | **6** | **4** |
| **No explanation** | 47 | 0 | 46 | 5 | 35 | 2 | 57 | 4 | 40 | 15 | 39 | 4 | 11 | 55 | 30 | 2 | **98** | **63** |
| **Blank** | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | **17** | **11** |
| **Total** | 67 | 1 | 64 | 24 | 55 | 6 | 73 | 22 | 59 | 23 | 53 | 21 | 18 | 72 | 46 | 20 | **156** | |
| **Total %** | 43 | 1 | 41 | 15 | 35 | 4 | 47 | 14 | 38 | 15 | 34 | 13 | 11 | 46 | 30 | 13 | | |

[a] Correct answer
[b] Correct explanation if applied correctly

as many students who think the output will decrease (64, 41% ) as there are who (correctly) think it will increase (67, 43%) when comparing a circuit with a doubled resistor (D) to the 'standard' one (A). The same is true when doubling the capacitor, although here more students incorrectly think a higher capacitance will lead to a lower output voltage ($C < A$) than there are who correctly think it will lead to a higher one ($C > A$) (73 (47%) and 55 (35%) respectively).

### Logical consistency among rankings

Although the results appear to be relatively random, Table 5.3 makes clear that the students' answers are very consistent and make logical sense. What we mean by 'logical sense' here is more than the order being possible (i.e. there are no students who say that $B > A$ and $C < A$, but still conclude that $C > B$). It refers to consistency in a students' *reasoning*. For example, there are 34 students (22%) who correctly think that doubling the resistor will increase the output voltage ($C > A$) and that doubling the capacitor will also increase the output voltage ($D > A$). Of those 34, 33 logically concluded that the circuit that has both the resistor and the capacitor doubled will have a higher output voltage than the original circuit ($B > A$). Only 1 of the 34 stated the illogical $A > B$. The latter is not contradictory in the same sense as the previous example, but it contains a different type of logical error: if doubling the resistor will increase the output voltage and doubling the capacitor will as well, then it makes no (logical) sense that doubling both will decrease the output voltage.

There is however one specific group of students who do give illogical answers in the sense described above: of the 42 students (27%) who (wrongly) think that doubling either the resistor or the capacitor will decrease the output voltage, 13 (31%) either think that doubling both will lead to an increase of the output voltage or to no change at all in the output voltage. So although over 90% of the students give a consistent (albeit most often incorrect) answer, it is unlikely that all 16 students who give an illogical answer simply made a guess: 13 (80% of this group) think that doubling the resistor or capacitor will decrease the output voltage, but still think that doubling both will either not affect the output or will result in an increase of the output voltage. Most likely, these students do not have a clear misconception, but instead use a different type of reasoning when comparing circuits C and D to circuit A than when comparing B to A.

Looking at the cross-table also shows that students can be logical when comparing circuit A to the other three, but still make mistakes when comparing circuits C (with a doubled capacitor) and D (doubled resistor) while still making logical sense. For example, of the 33 students mentioned earlier who (correctly) think that doubling the resistor and/or the capacitor will increase the output voltage, only 8 (25%) also say that doubling the resistor will have the same effect on the output voltage as doubling the capacitor (C=D). 14 of the remaining 25 think that $C > D$, which is a logical answer if one (wrongly) assumes that doubling the resistor will have a bigger effect than doubling the capacitor. Similarly, the remaining 11 think that $D < C$, which is consistent with the (again wrong) assumption that doubling the capacitor will have a bigger effect than doubling the resistor.

*Table 5.3: Cross table of all possible ranking combinations for the students who gave a complete answer.*

| | | **B>A**[a] | | | **B=A** | | | **B<A** | | | **Total C↔A** | **Total D↔A** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **C=D**[a] | **D>C** | **C>D** | **C=D**[a] | **D>C** | **C>D** | **C=D**[a] | **D>C** | **C>D** | | |
| **D>A**[a] | **C>A**[a] | 8[e] | 14[R] | 11[C] | 0 | 1 | 0 | 0 | 0 | 0 | 34 | 67 |
| | **C=A** | 0 | 3[e] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | |
| | **C<A** | 0 | 8[R] | 0 | 0 | 10[e] | 0 | 0 | 12[C] | 0 | 30 | |
| **D=A** | **C>A**[a] | 0 | 0 | 1[e] | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| | **C=A** | 0 | 0 | 0 | 0[e] | 0 | 0 | 0 | 0 | 0 | 0 | |
| | **C<A** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0[e] | 0 | |
| **D<A** | **C>A**[a] | 0 | 0 | 7[C] | 0 | 0 | 4[e] | 1 | 1 | 6[R] | 19 | 64 |
| | **C=A** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 3[e] | |
| | **C<A** | 3 | 2 | 0 | 1 | 4 | 3 | 4[e] | 16[C] | 9[R] | 42 | |
| **Total C↔D** | | 11 | 27 | 19 | 1 | 15 | 7 | 5 | 29 | 18 | 132 | |
| **Total B↔A** | | 57 | | | 23 | | | 52 | | | | |

[a] Correct answer
[e] Consistent answer if influence of R and C are equal in magnitude
[R] Consistent answer if influence of R is more important than that of C
[C] Consistent answer if influence of C is more important than that of R

### Correlating rankings with explanations

In terms of explanations the students gave, there are several conclusions that can be made. First of all, the students who thought that the resistor change and capacitor change would cancel each other out and explained their answer, all used classical circuit laws or a voltage divider. They usually made the mistake of thinking that the capacitor's impedance was proportional to its capacitance.

Secondly, 14 students (34% of those who provided an explanation) explicitly stated that the change in capacitance or resistance mattered more than the other or vice versa. However, there is no clear reason why students do this: some think doubling a component will cause an increase in output voltage while others think it will cause a decrease; some think the other component still matters but is less important while others think it has no influence at all; some cite signal properties (phase versus amplitude) as a reason while others refer to circuit laws to justify their answer. There is no clear pattern in the answers the students give using this approach, but it is a very interesting observation that deserves further investigation.

Next, it is remarkable that none of the students who used classical circuit laws without using a voltage divider managed to arrive at a correct answer. The students' explanations revealed several problems with the use of these circuit laws, including local reasoning, not knowing the impedance of a capacitor and the attribution of a higher importance to one of both components mentioned earlier. This was also observed during the interviews, with many of those students displaying similar problems.

A final observation has to do with the two types of explanation: based on recognizing the circuit as a filter and (implicitly) using classical circuit theory. In total, 9 students (22% of those who provided an explanation) explained their answer from a filter point of view. 2 of them managed to arrive at a fully correct answer. The remaining 32 students (78%) used an explanation based on circuit theory, of which only 3 managed to arrive at a correct answer (using a voltage divider approach). This indicates that the students who are using a filter approach are more successful than those using classical circuit theory (a success rate of over 20% as opposed to one of less than 10%). As the number of students using the filter-based approach is small, it is not possible to make any statements to generalize these results. Nevertheless, it is very interesting that there are so few students who managed to apply classical circuit laws correctly.

## 5.6 Discussion

In this study, we investigated students' conceptual understanding of first order $RC$ filters in the context of an introductory electronics course. We found that students struggle to analyze basic $RC$ filters after relevant instruction. In particular, tasks about the influence of the input signal and of different circuit components showed to be problematic. Considering that these students have already passed an earlier university level course of physics and are currently attending an electronics course, the number of students making these errors is high. In addition, relatively few students provided an explanation with their answer. The reason for this is unclear, although it could be because the questions were at the end of the questionnaire, which was limited in time (10-15 minutes) and did not count for any credit. It is therefore possible that students were less thorough or attentive answering these questions. [118, 119] That being said, the consistency and patterns observed in both questions indicate that the students did answer these questions seriously and put effort into answering them as correctly as possible.

A first important finding is that students in general think about these circuits using circuit laws rather than using a filter-based approach. While both are equally correct and useful in this case, it indicates that students are still more comfortable using the laws with which they are familiar. However, well known problems using those laws persist while students who do recognize the filter tend to perform better than their colleagues. That being said, the students who use a filter-based approach in the LPF question do not necessarily do so in the HPF question or vice versa.

Second, many students made mistakes known in literature. A very clear example is the current-based reasoning, which was also observed in several other studies.[66, 68] Another problem observed in earlier studies are the students who do not appreciate the frequency-dependent behavior of the circuit and think there is no difference between AC and DC input signals.[57, 62] However, an interesting new finding is that some students thought the question was about the RMS value, despite there not being any mention of power in the question. This did not occur during the interviews, so it is unclear why this is triggered.

When answering the high-pass filter question, it was very clear that students realized that both changing the resistor value and the capacitor value would have an influence on the output voltage. However, most did not know that doubling either component would lead to an increase in output voltage. In other words, they did not know the *direction* of the influence. Similarly, many did not know that both effects would be the same: doubling the resistor would result in the same output voltage as doubling the capacitor. The reasons for this are made more clear by the explanations provided with the student answers. Most often, students exhibited problems with classical circuit laws. One of the most important ones was that they had problems when analyzing circuits as voltage dividers, making three kinds of mistakes when doing so. The first was to think (implicitly) that the impedance of the capacitor is proportional to its value. The second is probably related to the local reasoning problem described in earlier studies: because the output voltage is measured across the resistor, students think that the resistor value has more influence than the capacitor value on the output voltage.[62, 66, 84] A final problem they have is that some students think the *capacitor* has a bigger influence than the resistor.

In general, several observations have been made that deserve further investigation:

- Even after lecture and lab instruction about filters, students tend to think about circuits using classical circuit laws rather than using a filter-based approach. Does this preference decrease over time? Does it depend on major (e.g. physics students using a different approach than engineering students)?;
- Despite passing an introductory physics course and studying electronics, students have problems applying those circuit laws when AC signals and frequency-dependent components are involved. Are the problems students have in AC caused by underlying misconceptions about basic laws in DC or do they see AC circuits as a completely different realm in which classical circuit laws are no longer valid?
- Some students think resistors have more influence than capacitors or vice versa. What is the cause of this?
- Some students completely ignore the frequency-dependent behavior of a circuit. Why do they ignore it?
- Most students know that both changing the resistor and capacitor will have an influence on the output of a first order $RC$ high-pass filter, yet do not know in what direction this influence will be, nor that the influence is the same for the resistor and the capacitor. Why do they think one is more important than the other? And why do they do know that both will have an influence?
- Many students did not manage to correctly assess the difference between AC and DC input signals for a low-pass filter. Are they capable of doing so for high-pass filters?
- Similarly, most students did not manage to correctly assess the influence of a changed component on the behavior of a high-pass filter. Are they able to do so for a low-pass filter?

Although many misconceptions about circuit laws are discussed in literature, current instruction does not seem to address those misconceptions: even after passing an introductory physics course and attending a lecture and laboratory session on $RC$ filters, students still make many mistakes even when, for example, using a voltage divider. More effort should be put into a correct conceptual understanding of basic circuit laws in introductory courses because a lack thereof hampers proper understanding of subsequent concepts. This is very clear from our research, which indicates that known problems with circuit laws directly translate to problems related to first order passive $RC$ filters even after relevant instruction. In future research, we will try to develop a laboratory to increase students' understanding of first order $RC$ filters, taking the findings discussed above into consideration.

When summarizing the general findings of this study, it is important to be aware of its limitations. A first observation is that rather few students included an explanation with their answer. So although there is good reason to assume that the students who did not provide an explanation used a similar reasoning to those who did, this is not certain. Therefore, conclusions related to the explanations given for the students' rankings have to be treated with caution. It is, for example, possible the students who did not include an explanation did all their work mentally, but used a different approach than those who did provide an explanation. Or maybe those who did not give an explanation simply guessed, although that seems very unlikely given the data. Second, we also decided to incorporate results that only provided an incomplete ranking (e.g. only stating that 'A=B' without mentioning the other circuit(s)), especially when analyzing the high-pass filter question. While these results are certainly valuable and have to be taken into account, it is also possible to treat them separately. A final aspect of filters not covered in this study is the *phase shift* they cause between input and output signals. Although we investigated whether or not students understood the influence of components (for an HPF) or AC opposed to DC input signals (for an LPF), more research is needed to understand whether or not students really understand all aspects of filters, including the phase shift.

# Chapter 6

# Video Observation as a Tool to Analyze and Modify an Electronics Laboratory

**Context**

The conceptual questionnaire used as pre- and post-test as well as, to a lesser extent, the interviews served to gain insight into what students eventually *learn* in terms of concepts from a laboratory session. In other words, those methods helped to identify the learning outcomes *after* the labwork, or what Sere et al. call the "effectiveness 2" of the lab [29]. However, neither methodology provides any insight into what goes on *during* the lab session itself. Observing the laboratory session in vivo could give valuable insight into what kind of activities students engage in and, more importantly, what they talk about during the laboratory sessions. It is not possible to accurately monitor students' thoughts during labwork, but what they say provides at least a good indication of what they are thinking. Therefore, several students were videotaped during the laboratory and their activities as well as their verbalisation were analysed. This chapter describes the analysis methodology as well as the results for the original labs. In addition, it briefly discusses the changes implemented in the laboratory as well as the results of these changes using the same analysis. A more detailed explanation of this new laboratory is in

Chapter 8. Its effects on the pre- and post-tests are discussed in Chapter 9.

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## 6.1 Introduction

Laboratories play an important role in science and engineering education. At the engineering technology faculty of our university 10% of the face-to-face time between teachers and students is during laboratory sessions (seen over the entire curriculum). In electronics subjects, the fraction of time spent in labs is even over 30%. The aim of those labs is usually to teach conceptual knowledge, in addition to the working of important devices [90]. To verify to what extent students learn concepts in laboratories, we investigated the lab on first order $RC$ filters, one of the first labs in electronics courses. The study presented in this article is part of a bigger research project in which we study how engineering students learn concepts in an electronics laboratory about first order $RC$ filters. One of the methods often used in literature to measure the resulting outcome of the lab is a pretest post-test design [44, 63], which we also adopted. Additionally, we conducted several interviews with students to probe both their understanding of the topic (first-order $RC$ filters) [96], as well as their ideas about the laboratory sessions themselves. However, the aim of this study is to gain insight into the students' behavior *during* the laboratory itself. Therefore, the focus of the present study is mainly the students' *activities* while attending a laboratory session. In order to gain insight into those, we videotaped several student pairs during the lab and analyzed the video tapes afterward by categorizing student behavior. Using video tapes of the laboratory sessions to analyze student behavior has several advantages. First of all, by observing the students in a "natural" environment, the analysis is based on their actual behavior rather than reported behavior from, e.g., interviews or surveys. Second, using a video (and audio) recording rather than a live observation protocol, for instance, allows reviewing these raw data often to ensure the analysis is done properly. As an added benefit, this raw data can be analyzed in multiple ways. Finally, by assigning student behavior to different categories, it is possible to analyze many recordings in a consistent way, without the need for a detailed transcript and lengthy discussions of the data. The aim of this analysis is to answer the following questions:

- What *activities* do students perform during lab sessions? (e.g., reading, discussing, measuring, etc.)
- What are students *talking about* during lab sessions? (e.g., content knowledge, technical problems, private life, etc.)
- How much time is spent on the different activities and topics of conversation?

The reason for the second question in particular is that "*talking about* [concept knowledge] *during labwork is assumed to be an important indicator for effective learning*" [33], based on social constructivist ideas and, in particular, Vygotsky's emphasis on speech during active learning as an important condition for this learning to occur [121].

The paper is organized as follows. It starts with a short literature overview in Sec. 6.2. A detailed description of the laboratory as well as the video-analysis is in Sec. 6.3. Based on this analysis (Sec. 6.4), the original lab was subsequently redesigned and the modifications were analyzed using the same methodology (Sec. 6.5), after which the reformed lab was adapted and analyzed again (Sec. 6.6).

## 6.2 Literature overview

### 6.2.1 Theory about learning

When developing a new laboratory session, we took two important factors into account. The first is that according to constructivist learning theory, learning is an *active* process, where a learner interacts with the subject matter to construct a mental model [122]. A new situation either can be incorporated in an existing mental model or can cause the mental model to be adjusted. Earlier studies have shown that the latter is harder, especially when a preexisting mental model of the situation contradicts the actual events [88, 123, 124]. A specific example of such a problem is the existence of confirmation bias [125]. This means that the results of an experiment are often interpreted in favor of a desired or expected outcome.

A second factor is the cognitive capacity of the human brain. While our long-term memory has a virtually infinite capacity, it is only possible to keep a limited number of pieces of information in working memory ("in mind") at the same time. When there exists a relation between those pieces of information, the load on the active memory (cognitive load) is increased, as every link is also a piece of information. However, by practice and familiarity with the topic, a set of interconnected ideas can be abstracted to a single entity, a so-called "schema," taking only one "slot" in the active memory [126]. When designing any learning environment, it is important to be aware of the limits of our working memory. An essential aspect is to reduce any cognitive load not related to the subject matter (extraneous load) as much as possible. On the other hand, it can be beneficial to increase the cognitive load in certain situations to focus the learner on a specific aspect of the subject (germane load). An example of such an approach, that also helps with schema construction, is so-called scaffolding: initially, a student is asked to complete a task where all but the final step is provided. In subsequent iterations, more steps are removed until the student is eventually able to solve the entire task without help.

A laboratory is an environment that naturally puts a rather heavy load on students' minds. There are various pieces of equipment, often unfamiliar to the student, with a lot of screens and buttons. Next, it is often hard to gather good measurements and certainly to interpret them in the context of the new physics law, chemical procedure or engineering design that is the learning object of the laboratory. In order to stimulate student learning as much as possible, it is important to remove as many distractions as possible and focus the students' attention on the learning object, in casu $RC$ filters.

### 6.2.2 Research about learning in labs

Despite the importance and cost of laboratory instruction in engineering education, relatively little attention has been paid to it in literature. However, there has been some work in the area of laboratory instruction in science education. One of the aspects that has been looked at are the goals of laboratory instruction. These are often unclear or vague and students are not always aware of their teachers' intentions with the lab [7, 11–13, 127]. Some goals are hardly different from the goals of the course in general, making one wonder about the specific role of laboratory instruction [14]. Previous research also pointed out that what teachers intend to teach in science laboratories is not necessarily what students learn during them [28].

In engineering education the focus of labs is mostly on integrating theory and practice [4, 23]. However, a lack of coherent learning objectives for labs has limited the effectiveness of laboratory instruction and has hampered meaningful research [7].

In the European Labwork in Science Education (LSE) project, the role of labs in science education and its effectiveness were studied [33]. This effectiveness is of course related to the learning objectives of the lab work. In this context, two types of effectiveness are distinguished, so-called “effectiveness 1 and 2” [29]. The first refers to how well the goals set for the lab by the teacher relate to what students do *during* the lab session itself. Effectiveness 2, on the other hand, is related to what influence student activities during the laboratory have on eventual student *learning* outcome seen over a longer period of time. Video analysis is a tool often employed to evaluate the effectiveness 1, in other words to look at what goes on in a (science) laboratory. Much of this research investigates the social interaction among students or between students and their teachers [35, 40], as is often done in pedagogical research [128]. Some of this research is done by researchers' detailed discussion of shorter episodes of the recordings [37, 39], but many studies use a categorization scheme to analyze student behavior [19, 21, 33].

The outcome of this type of research is often an identification of problems with the effectiveness of lab work. These include too much "cookbooklike" instruction, where students follow a set of predetermined steps specified in a lab guide. The students typically reflect very little on the setup or the data, believing they have to follow the instructions to get the right answer [10]. In many labs, there is no analysis or discussion of the data [10, 33, 43]. Niedderer *et al.* even call this a "missing link between theory and practice" [33]. However, this integration between theory and practice is precisely what others claim to be the aim of lab work in engineering education [4, 23]. What does happen in many laboratories is gathering data, which is not an activity that leads to a lot of talking about content knowledge [33]. While many authors do offer suggestions for improvement of laboratories, these suggestions are often vague or generic (e.g., to make sure the assessment is consistent with teachers' goals [10] or to use more innovative approaches [4]), while the more specific suggestions are not executed or studied in practice (e.g., to include calculations or rough data analysis in the measurement process[33]).

## 6.3 Context and methodology

This section contains a description both of the setting in which the study was performed as well as of the methodology used to analyze the labs. Section 6.3.1 gives a short introduction to the topic of the laboratories, first order $RC$ filters. Section 6.3.2 describes the setting of the research: the participants, their background and the context of the labs. Section 6.3.3 describes the actual methodology of the video analysis as well as the ways in which the data are represented.

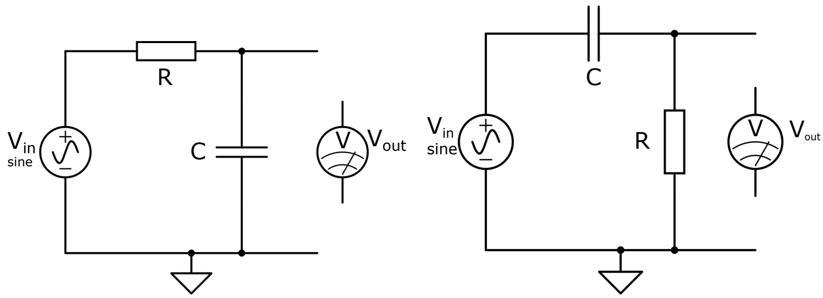
### 6.3.1 About $RC$ filters

Before presenting the research and findings, a quick introduction into the topic of $RC$ filters may be of interest. The circuits are those shown in Fig. 6.1. In a typical introductory physics course, a dc voltage source is applied to the input terminals of the low-pass filter [Fig. 6.1a]. The students then learn that the capacitor gradually charges: the voltage across the capacitor (at the output terminals) increases asymptotically to the value of the input voltage. The charging rate depends on the value of the resistor and the capacitor according to the following relation: $V_{out} = V_{in}(1 - e^{-t/RC})$. When the voltage source is then switched off, the output voltage decreases exponentially again. However, when the switching is done very rapidly, the capacitor does not have enough time to charge fully before starting to discharge again. When applying an ac voltage, something similar happens: the capacitor does not have the time to fully charge and as a result, the output voltage will be lower than the input voltage. The higher the frequency of the input signal, the less time the capacitor has to charge and the lower the output voltage will be. Something similar happens in the circuit shown in Fig. 6.1b, but now a signal with a higher frequency will pass undisturbed to the output terminals while one with a lower frequency will be attenuated. In addition to the influence on the amplitude, the filters will also cause a phase shift of the output voltage with respect to the input voltage. This phase shift will be negative (lagging output) for the LPF and positive (leading output) for the HPF. For both the high- and low-pass filters, the "border" between what is considered a high and low frequency is the so-called cutoff frequency $f_c$. This frequency depends on the value of the resistor and capacitor: $f_c = 1/2\pi RC$ for both LPF and HPF.

Another concept that the students encounter during the laboratory sessions are Bode plots. These plots have a logarithmic $x$ axis on which the frequency of the input signal is indicated. The $y$ axis shows the voltage gain (the fraction of the output amplitude over the input amplitude), most commonly expressed in decibel (dB). A second plot shows the phase shift of the output signal with respect to the input signal in degrees, again as a function of (logarithmic) frequency. On such a plot, one can see that the gain at the cutoff frequency is -3dB, while the phase shift is 45°(lagging for LPF and leading for HPF). An example is shown in Fig. 6.2.This type of plot is widely used in electronics to design circuits of which the frequency behavior is important, such as in filtering for audio applications, noise removal in medical signals, or radio telecommunication.

### 6.3.2 Participants and educational context

The study was performed at three different campuses of the faculty of engineering technology at our university. The focus was on an introductory electronics course, scheduled in the second year of the bachelor curriculum. At campuses 1 and 2, the students had chosen electronics or electromechanics as their field of study while at campus 3 the students had not chosen a specialization yet.




(a) Low-pass filter (b) High-pass filter

*Figure 6.1: First order RC filters.*

Although details of the curricula at the campuses differ, at all three campuses this introductory electronics course included several lab sessions in addition to traditional lectures. While around 100 students were typically enrolled in a course, the lab sessions took place in smaller groups of under 20 students working in pairs under the supervision of one teaching assistant (TA). One of the first of those sessions was on first order $RC$ filters.

The content of the sessions was very similar at all campuses and is described in more detail in Sec. 6.4.1, while some circumstantial factors are outlined below and in Table 6.1. First of all, the duration of the labs was different at the three different campuses. Second, the students at campus 1 and 2 had to write a (graded) report, which was available to us. The students at campus 3 did not write reports but instead had a lab examination at the end of the semester. Finally, the students at campuses 1 and 2 had to make a computer simulation of their circuit and compare their measurement data with their simulation. The students worked in pairs during the lab and also wrote the reports together. All labs had a lab guide with instructions on the measurement procedures, the equipment and underlying theory. This lab guide also contained a list of goals for the labs, which were the same across all three campuses: to learn how to work with lab equipment (oscilloscope and function generator), to learn to construct and use a Bode plot and to gain insight in first order $RC$ filters. These goals are explicitly stated in each of the lab guides.

In autumn 2012 and spring 2013, the original labs were observed at all campuses. In autumn 2013, 6 additional labs were observed in their original version at campus 3. Section 6.4 describes the findings of those sessions. In spring 2014, pilot versions of the reformed labs were tried out at campuses 1 and 2, described and analyzed in Sec. 6.5. In autumn 2014 and spring 2015, a final version of

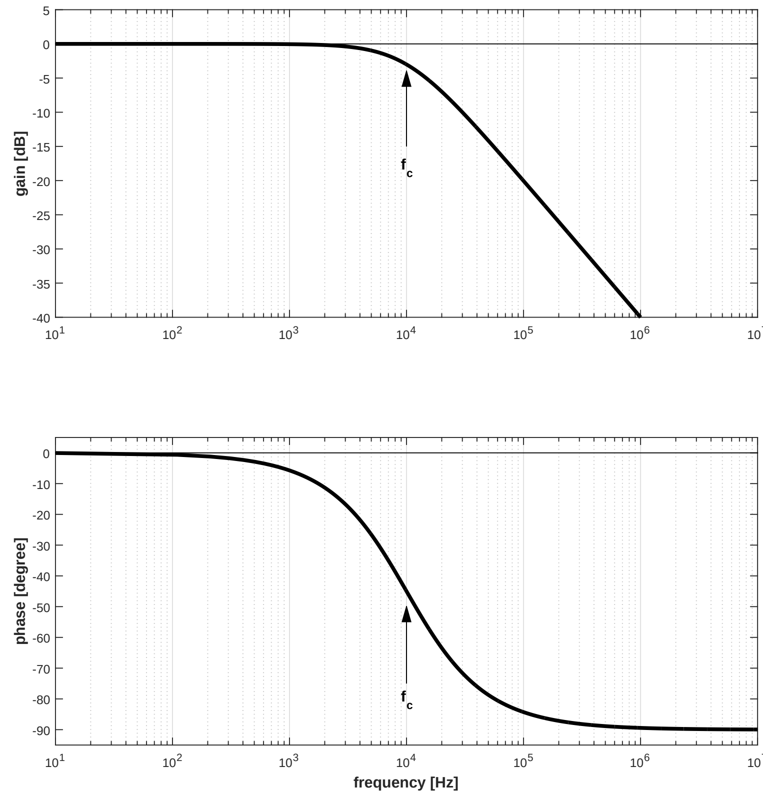



*Figure 6.2: Example of the Bode plot of a low-pass filter. One can see that at the cutoff frequency (here 10 kHz), the gain is -3 dB and the phase shift is -45°. It is also clear that the phase shift will be limited to -90°.*

the reformed lab was administered at campuses 1 and 3 (campus 2 chose not to participate anymore). This version is described and analyzed in Sec. 6.6. Table 6.1 shows an overview of the student pairs filmed and the settings, listed by campus. At campus 1 and 2, a conceptual test was administered at the beginning of the lab, taking around 15 min out of the total lab time.

*Table 6.1: Overview of settings and number of student pairs filmed organized by campus*

| Campus | Field | Duration | Simulation? | Report? | $N_{orig}$ | $N_{pilot}$ | $N_{Final}$ |
|---|---|---|---|---|---|---|---|
| 1 | Electronics | 2h 00 | yes | yes | 2 | 4 [a] | 4 |
| 2 | Electronics | 3h 00 | yes | yes | 2 | 2 | 0 |
| 3 | General | 1h 30 | no | no | 9 | 0 | 6 |
| | | | | total | 13 | 6 | 10 |

[a] 2 prepared and 2 unprepared.

### 6.3.3 Video analysis

By videotaping students during the lab, we wanted to gain insight in student activities, as well as in their thought process. The aim is to find out what students spend their time on during the labs (manipulating equipment, performing measurements, etc.) as well as what they talk about (concepts, technical knowledge, etc.). The latter is the best indication available for what they are thinking about without interfering with the natural course of the lab session. Moreover, talking about content knowledge is also considered an indicator for learning [47]. In addition, we wanted to find relations between what students were doing and what they were saying in order to find an indication of what type of activities trigger meaningful conversation.

We therefore used a category-based analysis of the tapes based on the so-called 'Category Based Analysis of Videotapes from Labwork' (CBAV)[33] and, to a lesser extent, on the categories used by Warren [40]. The CBAV approach was chosen because the research questions asked in those studies are similar: how much time is spent on a certain activity and which activities promote talking about content. Especially the latter was an important attribute of the CBAV as the relation between the activities and student thinking is of particular interest. Additionally, the environment of both the CBAV study and the study presented here is similar (physics laboratories). An additional benefit of the approach is that encoding can be done in nearly real time, eliminating the need for lengthy discussions or transcriptions of the video material.

During every lab session, one or two pairs of students were videotaped. They were selected at random and did not know in advance they would be videotaped. The students and the TA signed an informed consent form before starting the recording. The camera was positioned in between both students, looking "over their shoulders." Sound was recorded by either a dedicated table microphone or two clip-on microphones. Neither the video tape nor informal observation in the lab room indicated any significant interference of the recording process with the normal course of the laboratory session. For the analysis, all videos were divided into 30 sec time slots and each slot was assigned one *context* category and one *verbalization* category. The context refers to what students are *doing* during the time slot, while the verbalization refers to what they are *talking* (or reading or writing) about. This verbalized knowledge is considered an indicator for student thinking.

An overview of the context categories used is in Table 6.2. Table 6.3 shows an overview of all the verbalization categories. A short explanation and an example of every category is in Appendix C. After using the same categories as the CBAV and analyzing the results, it was found that some categories were obsolete, such as the "computer measurement" (CME) context category, which is irrelevant for our laboratory. Other aspects were hard to fit into a category and required a new category, e.g. a discussion about the exact measurement value triggered the creation of the "measurement reading" (MR) verbalization. Another such example was the "data discussion" (DD) category: the students were pointing at their measurement results and discussing them without writing, measuring or other activities. Other categories were too broad for our purpose, for example the "3P" category (used when a third person intervened in the pair) in which there was no distinction between an intervention of the TA in the specific observed pair ["third person" (3P) in our scheme] or a general address of the TA to the entire class ["blackboard" (BB)]. Moreover, we added the "no verbalization" (NV) category. This clarified whether a time slot without a verbalization category assigned to it was a mistake in the analysis or a period during which the students were not talking. A final adaptation was made in the verbalization categories regarding data discussion: we chose to distinguish between different ways in which the data were discussed: just describing a trend ["geometrical" or GD], comparing a (set of) measurement(s) to a given example in the lab manual ["example-based" or ED] or analyzing based on knowledge of the underlying principles ["content-based" or CD].

After author P.C. coded the initial set of videos, an extensive code book was created with a detailed description of the categories, including examples. The others then used this code book to analyze a video each and subsequently compare their results with those of P.C. We used Cohen's $\kappa$ to verify the interrater reliability[129]. Initial coding revealed confusion between the "mathematical knowledge" verbalization and the "calculation" context category, which was resolved after clarification and renaming (to "measurement processing" context). A second issue, also noticed by Niedderer *et al.*, is that sometimes an activity extends from the middle of one time slot to the middle of the next. This can cause a "phase shift" in the coding of two coders, one assigning the activity to the first and the other to the second time slot. Eventual Cohen's $\kappa$

for the context was 0.68 and that for the verbalization was 0.62, indicating a "substantial" agreement between both raters [114]. To ensure a uniform coding, the analysis discussed in this paper is based on the coding of all videos by P.C.

The categorization scheme described above can be used in various ways to analyze laboratories. The first is to look at the context and verbalization separately to verify *how often* a certain activity happens or a type of verbalization occurs. Second, either can be plotted on a time line to see *when* it occurs, as well as which one follows another in time. Finally, in order to find out *what students are talking about when performing a certain activity*, it is possible to make a cross table between contexts and verbalizations. For example, the latter approach can give insight into the activities that trigger content-based discussion, helps to determine what the TA is talking about in front of the class or why the students call the TA for help.

*Table 6.2: Categories for contexts. These are explained in more depth in Table C.1 in Appendix C.*

| Code | Name |
|---|---|
| O | Other |
| 3P | Third person |
| LG | Lab guide |
| BB | Blackboard |
| WD | Write & discuss |
| MA | Manipulating apparatus |
| ME | Measurement |
| CB | Building computer model |
| CS | Computer simulation |
| MP | Measurement processing |
| DD | Data discussion |

*Table 6.3: Categories for verbalizations. These are explained in more depth in Table C.2 in Appendix C.*

| Code | Name |
|---|---|
| TK | Technical knowledge |
| CK | Content knowledge |
| TC | Technical and content intertwined |
| MK | Mathematical knowledge |
| GD | Geometrical description |
| CD | Content-based description |
| ED | Example-based description |
| MR | Measurement reading |
| NV | No verbalization |

## 6.4 Analysis of original lab

### 6.4.1 Description

As mentioned earlier, the laboratories are part of an introductory course in electronics. The topic of first order $RC$ filters was already covered in lecture(s) prior to the laboratory. The main idea of the original lab sessions themselves was to measure the input and output voltage of a known $RC$ filter as a function of the frequency and to describe it by using a Bode plot. At the beginning of the labs, the TA gave an introduction covering the theory, the equipment and the measurement procedures. Then, the students received a (known) resistor and capacitor, configured as a low-pass filter (LPF) or a high-pass filter (HPF). They applied a specific (ac) voltage by means of a signal generator and measured the output voltage as well as the phase shift between the input and the output signal using an oscilloscope. By varying the frequency of the input signal and performing repeated measurements, the students could then calculate the gain in decibel (dB) for every frequency and construct a Bode plot. While they were all required to compare their measurements to their theoretical expectations, only the students at campuses 1 and 2 also did simulations of their circuit to compare their measurements with. Students were required to comment on their measurement results and indicate how they differed from the theoretical and/or simulated results and to come up with an explanation for those differences. The differences can be attributed to a variety of causes, most notably a tolerance on component value (typically 5%-10%), measurement errors (it is hard to read an amplitude or phase visually on an oscilloscope screen) and input inaccuracies (the function generator's amplitude and frequency are not exact). As a result of these errors, the cutoff frequency will typically not be where it was expected and there will be a certain degree of noise on the measurements, causing (small) conflicts between, e.g., a phase shift of 45° while the gain is -2 dB.

### 6.4.2 Results

Figure 6.3 is an overview of how often every category appeared in the original labs. The bins are the contexts in the left figures, while the colors show verbalization. The right column has the reverse: bins for verbalization and color for contexts. The results at campuses 1 and 3 were rather similar, while those at campus 2 differed and are discussed separately.

#### Campuses 1 and 3

At campuses 1 and 3, the labs typically started with an introduction by the TA (context BB). This introduction consisted of two main parts, a theoretical one (verbalization CK) and a technical one (verbalization TK). At campus 3, the theoretical part also included a purely mathematical explanation of the theory (verbalization MK). The technical part at both campuses consisted of an introduction to the lab equipment, mainly the oscilloscope and function generator. The entire introduction took around 20 min, which corresponds to around 20%-25% of the total lab time. Together with shorter episodes later during the lab, the total time a TA talked to the class as a whole could rise to over 50% for some labs, especially at campus 3.

The time the students are working in pairs starts by setting up their equipment (context MA). During this phase, they often switch to their manual (context LG) and sometimes to the TA or fellow students (context 3P) for help with technical problems (verbalization TK). After that, most of the students' time is spent conducting measurements (context ME). During the measurements, most of the verbalization is reading off values (verbalization MR), although sometimes there are comments relating different measurements to one another (verbalization GD). At campus 3, however, very little time is spent performing measurements, most of the time there is used to set up the equipment (context MA) and little time is left to gather measurements (context ME).

During the lab, hardly any measurements are processed or plotted (context MP). In turn, this leads to very little data discussion (context DD). The discussion that does happen is either graphical (verbalization GD) or a comparison with an example in the lab guide (verbalization ED). Only rarely is it related to content knowledge (verbalization CD). The students at campus 1 also did not make a computer model of their circuit (context CB) and subsequently did not do any simulations (context CS) during the assigned lab time despite it being a requirement of the lab.

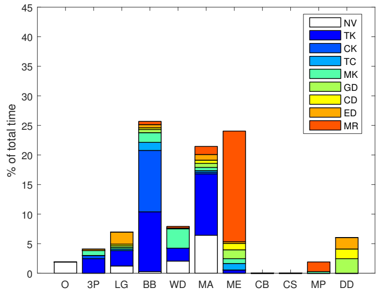
As a lot of time is spent manipulating equipment (context MA) or performing measurements (context ME), an obvious consequence is that most verbalization is technical knowledge (verbalization TK) or reading off measurements (verbalization MR). It also appears that a sizable part of the lab is spent discussing pure content knowledge (verbalization CK). However, closer inspection clearly indicates that this is mainly (over 90%) done by the TA (contexts BB) or is initiated by the TA (context 3P). Very often there is no verbalization at all, most often when the students are working with their equipment (context MA). The only content knowledge the students use themselves is expressed mathematically (verbalization MK), without indication they understand it also conceptually.

#### Campus 2

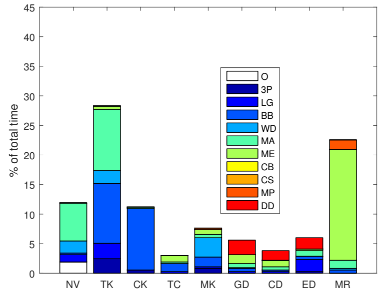
At campus 2, the introduction is very short, since the students here already worked with an oscilloscope before and were required to prepare for the lab. The students there also started by constructing a computer model (context CB) before doing any measurements. During this model building, they often copied code from their manual (verbalization ED) and struggled to adjust it to their needs. Afterward, they performed the lab much like the students at the other campuses, starting with setting up their equipment (context MA) and then performing a long series of measurements (context ME). They spent more or less the same amount of time on setting up their equipment (context MA) as their colleagues at the other campuses (in absolute terms). During the measurements (context ME), they do not process or discuss them at all. However, they did process (context MP) and discuss (context DD) them afterward, most often from a content point of view (verbalization CD) and comparing their measurements to values of their simulations (verbalization GD).

### 6.4.3 Discussion

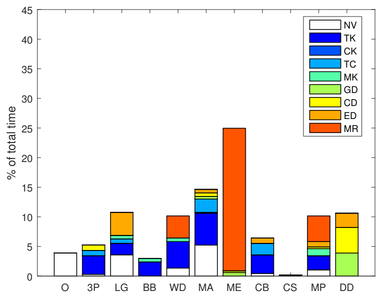
At the beginning of the laboratories at campuses 1 and 3, there was a long introduction by the TA, which covered both the theoretical aspects of $RC$ filters and a demonstration of the lab equipment. Afterward, most of the time at those campuses was spent measuring and dealing with lab equipment. To explain



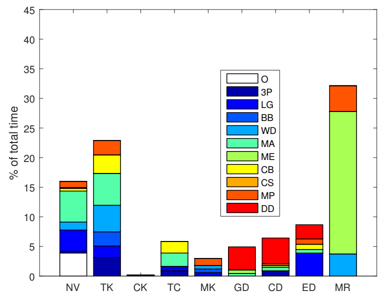

(a) Contexts for students at campus 1 with verbalization color-coded



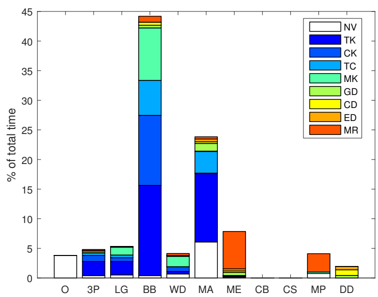

(b) Verbalizations for students at campus 1 with context color-coded



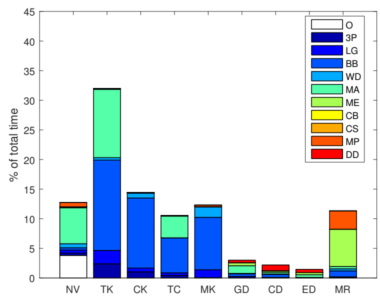

(c) Contexts for students at campus 2 with verbalization color-coded




(d) Verbalizations for students at campus 2 with context color-coded




(e) Contexts for students at campus 3 with verbalization color-coded




(f) Verbalizations for students at campus 3 with context color-coded

*Figure 6.3: Results of original labs. All percentages are the total of all pairs at the different campuses. Left are contexts in bins with verbalization marked by colors (6.3a, 6.3c and 6.3e), while right are verbalizations in bins with the contexts marked by colors (6.3b, 6.3d and 6.3f). The rows are campus 1 (6.3a and 6.3b), 2 (6.3c and 6.3d) and 3 (6.3e and 6.3f), respectively.*

this observation discussed in Sec. 6.4.2, we reviewed the relevant sections of the recordings in more detail.

A first observation was that many students had a lot of trouble configuring the oscilloscope correctly and struggled to read measurements, including amplitude and phase. An example is the following statement made by one of the students, 40 min into his lab session:

STUDENT1: *9 marks is one full cycle, so that is 180°*

At campus 3, this even led to students not able to gather enough measurements to draw any conclusions from. The specific problem with oscilloscopes has also come to the attention of Bernhard [130] and was mentioned by several students during the interviews.

A second problem that emerged is that the students at all campuses rely heavily on a set of example measurements in their lab guides. Many students actually built the same circuit as in the example and copied the input frequencies and those who built a different circuit often did not choose their input frequencies accordingly. An example are the measurements handed in by one of the students at campus 1 shown in Table 6.4. The students here had a filter with a cutoff frequency around 2 kHz, but did not adjust their measurement grid accordingly.

*Table 6.4: Example set of measurements as taken by one of the pairs during the original lab at campus 1.*

| f [Hz] | A [dB] | $\phi$ [deg] |
|---|---|---|
| 10 | -44 | 90 |
| 100 | -28 | 86 |
| 1000 | -8 | 65 |
| 2000 | -3 | 48 |
| 5000 | -1 | 23 |
| 7000 | -1 | 21 |
| 10 000 | -1 | 14 |
| 20 000 | -1 | 7 |
| ... | ... | ... |

A third common problem that is illustrated by student measurements is that students often do not judge their measurements critically. An example is from two students who had a low-pass filter with a cutoff frequency of "5894.6 Hz." They measured their output signal at 5846 Hz and found that their phase shift was -48°while the gain was -20.35 dB. They did not realize it is impossible to have a phase shift of about -45° with a gain that is this different from -3 dB.

A next aspect worth mentioning stems from the interviews, where students said that they only processed their measurements and did the simulations at home, after the lab. Only then they would discuss the measurements, sometimes realizing they did something wrong during the lab, but unable to correct their measurements without access to the lab. In other words, not processing the measurements during the laboratory itself prohibits any reflection or discussion about them.

Finally, the evaluation of the measurements in the lab reports, if done at all, was very superficial. An example is "the measurements agree with the simulation" in their report. The latter is an indication of confirmation bias: instead of observing that their measurements are somewhat different from theory and looking for the cause, the students have the "correct" answer in mind and fail to see anything else. A clear example is a set of measurements with the following sequence of input frequencies: $(\cdots)$ 2, 3, 4, 5.895, 6, 7, 8 kHz $(\cdots)$. It is rather strange to have a series of nicely rounded frequencies with the exception of one very precise frequency (the cutoff frequency). This corresponds strongly with the findings of Niedderer *et al.* [33]:

> "All findings together indicate, that data analysis often is not an important part of lab work. These results would also be in line with the assumption, that students mainly aim at 'gathering data' and not at 'reflecting theoretically' which can be seen as one way 'to link theory to practise'."

It appears that similar observations can be seen here: students spend almost all their time gathering measurements, mainly because they seem to have problems using the oscilloscope.

However, we suspect that the main reason students spend little time discussing content (verbalizations CK or CD) is most likely that there are many aspects of the lab in addition to the content that are new to the students. This has been observed by Niedderer *et al.* in a different laboratory course on electronics, where "*Learning to experiment, to solve problems with the apparatus and to apply new theory was too much at one time.*" [44]. In this case, it is the first time they encounter ($RC$) filters, which they have to measure using equipment they have never used (oscilloscope and function generator) and subsequently have to process the data in a way they never did before (Bode plot). We hypothesize that this leads to the students being overwhelmed, making it hard for them to learn about any of those aspects. In other words, many students suffer from a cognitive overload: there are too many unfamiliar aspects to the laboratory that they have to keep in mind simultaneously. At campuses 1 and 3, the students also did not review $RC$ filters before entering the lab as they were not required to prepare. This is less evident at campus 2, where the students did process and discuss their measurements. Besides having enough time for that, the students at this campus were also required to prepare for the lab by answering a series of theoretical questions about $RC$ filters. Moreover, this was not the first laboratory in which they used oscilloscopes, although they still seemed to struggle with their usage.

## 6.5 Analysis of the pilot version of the black box lab

### 6.5.1 Description

One of the first problems with the original lab was that students were not prepared at all at campuses 1 and 3. A second problem was that students were not familiar with the equipment and, consequently, spent a lot of time setting it up (context MA) and gathering measurements (context ME), sometimes not even managing the latter. A final problem was that students did not process their measurements during the lab and so did not manage to discuss them in order to "link theory to practice" [33]. An exception are the students at campus 2, who do process their measurements during the laboratory sessions.

As discussed in Sec. 6.4.3 above, we hypothesize that the problems in the original laboratories were caused by overwhelming the students with too many unfamiliar things at the same time, including new equipment, processing and actual content. The main idea of the reformed lab is to try to avoid the students being overwhelmed by separating some new aspects from the actual lab to a preparation. This way, their knowledge base at the start of the lab is expanded, lowering the cognitive load during the laboratory session itself and freeing up cognitive capacity for the main topic of the lab, namely the $RC$ filters themselves.

To ease the students into two new aspects, namely, the use of the oscilloscope and Bode plot, they were asked to prepare for the lab by doing two exercises made available online before the lab. The first exercise used a Matlab oscilloscope simulator, which the students could use to practice both reading and configuring a virtual oscilloscope. The simulator generated two random sine waves and set the “buttons” of the oscilloscope in such a way that it was impossible to read the signal properly. The students then had to adjust the settings so they could measure the amplitude and frequency of both, as well as the phase shift between them. This simulator is shown in Fig. 6.4. The second exercise showed a set of measurements and asked the students to sketch a possible Bode plot for them. They were required to hand in the preparation at the beginning of the lab. These exercises aim to make the students more familiar with two new aspects during the lab, helping them to already create a “schema” for these aspects in advance. That way, the extraneous cognitive load is decreased, freeing (active) memory for the actual laboratory subject. Additionally, an increased proficiency with especially the oscilloscope should decrease the time spent measuring, freeing not only memory capacity, but also *time* to discuss the measurement results.

The lab itself was also changed. Instead of getting known components in a known configuration, all students got a “black box” like the one in Fig. 6.5. The box contained a resistor and capacitor from a short list of possible values in an unknown configuration (LPF or HPF). The first task of the students was to determine the content of this black box by using a function generator and oscilloscope as before, in addition to an Ohmmeter (multimeter). They were also given the list of possible component values. By using (literally) black boxes, any possible confirmation bias is eliminated. This approach also increases the germane cognitive load by forcing the students to properly process and interpret their measurement results. This idea of using black boxes in electricity laboratories has been proposed in literature before [131, 132], but only rarely has the effect of using this approach been studied [133]. To our knowledge, it has not been tried for $RC$ filters.

Second, an additional resistor or capacitor with an identical value to the original component could be added in series or parallel with the original component by means of a switch on top of the box. An example of a complete circuit is shown in Fig. 6.5b. This example shows an LPF with a resistor added in parallel when the switch is thrown. This idea of adding an extra component was inspired by the so-called “variation theory” approach used by Bernhard [51]. In this approach, learners are confronted with a change in one variable while the others are kept constant. The aim is then for the learner to find out what effect this change will have. Here, the students were told the switch added either a resistor or capacitor with the same value as the original circuit, in series or parallel to the same component, but not which one exactly. They had to find out the exact configuration of the circuit with the switch themselves.

The ideal reasoning in the laboratory starts by applying a known sine wave to the input and measuring the resulting output signal. From this, one can construct a Bode plot of the filter in the black box, much like the approach used in the original labs. The measurements indicate whether the box contains an LPF or HPF, either by only looking at the phase or by looking at the amplitude as a function of the frequency. This in turn makes it clear between which two terminals on the box the resistor is situated. Using a multimeter, one can then measure the value of $R$. By taking more measurements at the appropriate frequencies, the cutoff frequency ($f_c$) can be pinpointed, which in turn depends on the product of $R$ and $C$. Since the value of $R$ and $f_c$ are known, $C$ is found by using $f_c = 1/2\pi RC$. Knowing all component values as well as the type of filter, the entire configuration is now known. After flicking the switch, the same approach can be used. In this case, a change in resistor value makes it clear immediately what the switch does, while if the capacitor is changed, one can use the change in $f_c$ to determine the exact configuration.

The manual of the lab was rewritten to adjust the instructions to the black box approach used. In addition, the set of example measurements was removed and several conceptual qualitative questions were added. Examples are "what does the ac setting on an oscilloscope do" or "how would you build a bandpass filter." These questions are inspired by the questions asked to students in the "Physics by Inquiry" models developed by McDermott and Shaffer [97, 99]. The students at both campuses were still required to make a computer simulation, as well as to hand in a report of their lab.

### 6.5.2 Results

As indicated in Table 6.1, four pairs of students at campus 1 and two pairs at campus 2 were recorded while performing the pilot lab. At campus 1, two initial groups of students did not prepare for the lab. After email reminders to the other groups, the next two did prepare. This resulted in two different sets of data for this campus in the pilot version of the lab. The results of all six pairs are shown in Fig. 6.6.

By comparing Figs. 6.3a and 6.3b with Figs. 6.6a and 6.6b respectively, it is clear that the unprepared students behaved similarly to the students during the original labs: they spent most of their time struggling with equipment (context MA) or performing measurements (context ME). When discussing their data, however, (context DD), they did so more often from a content-based point of view (verbalization CD) than during the same context in the original laboratory. More concrete, this means that they, for instance, realize that when

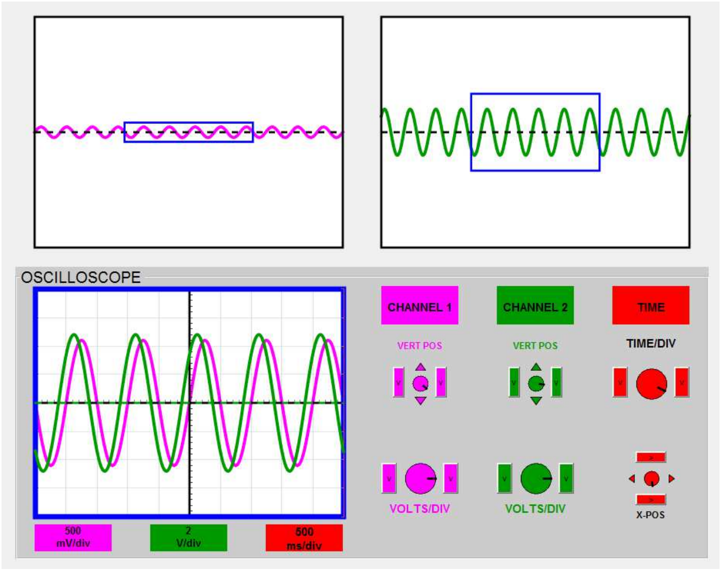
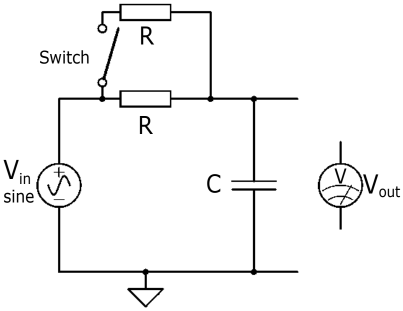



*Figure 6.4: Original oscilloscope simulator. The screens on top show the "total" signal, with portion shown on the oscilloscope screen in the blue rectangle.*


(a) 'Black box' itself




(b) Underlying circuit

*Figure 6.5: Black box used in the new labs. 6.5a The box itself: The black connectors are the ground level, while the red ones are the signal. The input is on the left, output on the right. Every box is unique and has an individual number (here 15). An example of an underlying circuit is shown in 6.5b.*

they measure a gain of -3 dB, this means their input frequency is the cutoff frequency. This was opposed to the original laboratory where one pair simply observed that the gain "kept decreasing." Again, they did not process their measurements (context MP) during the lab, nor did they do any computer simulation (context CB and CS), as is clear from Fig. 6.6a. The introduction by the TA (context BB) was more or less the same as in the original labs.

The prepared students spent about as much time as their colleagues measuring (context ME), although they were more likely to comment on their measurements (verbalizations CD, GD, and ED) while measuring. They also did not spend any more (or less) time processing their measurements (context MP) and did not do any simulations either (contexts CB and CS). They did spent more time reading their lab manual (context LG) instead of talking to the TA or fellow students (context 3P).

### 6.5.3 Discussion

A lot of time in the new laboratory was still used for the introduction by the TA at the beginning of the lab, shortening the time available to the students to gather and analyze their measurements. Additionally, most of the time is still spent struggling with equipment and gathering measurements. Informal discussion with the students revealed that they found it difficult to work with the simulator as it did not include any information on how to read a signal from an oscilloscope. Also, there did not seem to be much difference between prepared and unprepared students: they spent more or less the same amount of time gathering measurements and hardly any in processing them.

However, looking at the time line sheds light on the reason why even the prepared students spent so much time measuring: they managed to perform two sets of measurements in the same amount of time, essentially performing twice as many measurements. The first time with the switch in the first position, the second time with the switch in the second position. Figure 6.7 shows this very clearly for one of the observed pairs (it was equally clear for the other pair). The very brief measurement in between both blocks is the measurement of the resistor value. This is a clear indication the preparation helped to speed up the measurement process.

Another improvement overall was that all students thought about which measurement point to take next from a content perspective instead of using the example from the manual. This was indicated by reviewing the video data for when the students discussed data from a content-based point of view (verbalization CD) while gathering measurements (context ME). In practice, this means that the students behaved similarly to both students in the discussion below, who had a low-pass filter with a cutoff frequency between 1 and 10 kHz. They measured a phase shift of -18° at 1 kHz and just measured a phase shift of -68° at 10 kHz:

STUDENT 1: *Ah, so we're past the cutoff already.*

STUDENT 2: *Yeah, our cutoff frequency is somewhere here* [between 1 and 10 kHz].

STUDENT 1: *Then we should do some more measurements in between those two.*

However, the recordings also showed that most students still did not actually process and properly discuss their measurements, nor did they do any simulations. Consequently, they did not compare their measurements to the simulations or theoretical values during the laboratory sessions themselves.

## 6.6 Analysis of the final version of the black box lab

### 6.6.1 Description

As indicated in Table 6.1, a final version of the black box laboratory was introduced at campuses 1 and 3 (campus 2 withdrew from the project). Four pairs of students were recorded at campus 1 and six were recorded at campus 3.

The preparation was kept the same as with the pilot version of the lab, although the oscilloscope simulation was altered. In the new simulation, a scaffolding approach was used by adding a "learning unit." In the learning unit, shown in Fig. 6.8c, the students can practice reading the frequency, amplitude or phase of random signals with various levels of difficulty. In a first step, labeled "read" in Fig. 6.8a, the buttons of the oscilloscope are properly configured, so the student only has to read the signal parameter. The simulator would then indicate whether or not the answer was correct. In a a next step, one set of buttons [time ($x$) or amplitude ($y$)] is off in both the zoom and the position. This means that the student first has to adjust one set of buttons before being able to read the signal properly. In a final step, both sets of buttons are off, requiring the student to adjust both simultaneously before being able to read the parameters properly. In addition, a pane was added with an explanation on how to read each parameter. Whenever the students felt they were ready, they could then take the "test." As shown in Fig. 6.8b, this test only showed an "oscilloscope" screen and its buttons. The student then had to read all parameters, fill them in on their preparation sheet and hand it in at the beginning of the laboratory.

The lab session itself was altered in the sense that instead of asking the students to measure the circuit with the switch in both positions, they only had to measure one. They would then get a Bode plot of the second circuit and were asked to determine what change the switch caused in their circuit based on their own measurements and the given Bode plot. The "ideal reasoning" here is similar to that of the pilot laboratory. In order to find out what the switch does, the students have to compare their measured cutoff frequency with the one of the Bode plot, which should be either half or double their measured one. Then, they have to measure the resistor value. If it has changed, the effect of the switch is clear: either a resistor was added in parallel (lower $R$, but higher $f_c$) or series (higher $R$, lower $f_c$). If it is the same, a capacitor was added in series (halving $C$ but doubling $f_c$) or parallel (doubling $C$ and halving $f_c$). This adjustment was done for practical reasons at campus 3, where the students only had 90 min to complete the lab. The students at this campus also did not have to write a report, so they were asked to hand in their measurements and both circuit diagrams at the end of the lab. At campus 1, similar changes were made, including adding the Bode plot of the second circuit and asking the students to hand in some measurement results at the end of the lab. Giving the students the Bode plot of the second circuit was also meant to reduce the time spent measuring, giving them more time for discussion. Asking the students to hand in their measurements and conclusions (circuits) at the end of the lab forced them to also process their measurements and to think about them during the lab session itself. At campus 1, P.C. served as TA for the lab and reduced the time spent on the introduction.

### 6.6.2 Results

The results of this lab are shown in Fig. 6.9. The introduction by the TA was shorter than in the original lab. At campus 1, P.C. taught the lab, shortening the introduction. At campus 3, the same teachers who taught the original laboratories gave the same introduction, but the change in the laboratory caused them to keep the introduction shorter as well. There was more time used by the students at campus 3 to perform more measurements (context ME) as well as to process them (context MP). They then also analyzed the measurements (context DD) and discussed them from a content-based point of view (verbalization CD). At campus 1, the students spent less time performing measurements (context ME) than in the first version of the new lab. At this campus, more time was spent on three things. The first of these was the computer simulations: half of the students made their computer models (context CB) in the lab instead of postponing it to after the lab. Second, they spent more time setting up their equipment (context MA). Finally, the students also discussed their measurements (context DD) a lot more during the lab, mostly from a content-based point of view (verbalization CD).

### 6.6.3 Discussion

The preparation helped to both speed up the measurement process and the data processing (Bode plot). Reducing the number of required measurements by giving the Bode plot of the second circuit also helped to reduce the time spent measuring. The time the students had at their disposal was further increased by reducing the introduction of the TA. This extra time was spent on discussing the results of their measurements and the exact circuit configuration as well as building a computer model (at campus 1).

We found it surprising that the (prepared) students at campus 3 spent *more* time with their equipment (context MA), which was not seen in the pilot version of the black box laboratory. Reviewing the relevant sections of the video recordings showed this was due to one of the added qualitative conceptual questions which asked what the ac setting on an oscilloscope did. The students would then try this out on the oscilloscope while discussing this question, resulting in an increased amount of time spent manipulating equipment (context MA).

## 6.7 Conclusion

As a conclusion, we would like to evaluate both the methodology used (video observation) as well as the idea of using a black box teaching approach in a laboratory environment. Finally, some suggestions for future research are given.

### 6.7.1 Video analysis

The methodology used here allows us to gain insight in student activities as well as verbalizations during laboratories. The dual analysis of both what students are doing and what they are saying makes it a good tool to assess the interaction between student activities and speech, which is an expression of their thoughts. It made it possible to not only *assess* a laboratory session from this point of view, but also to *modify* it and to verify the changes made in a structured and consistent way. The methodology ensured it was possible to compare both laboratories in a richer way than a pretest post-test design allows by showing what students spend their time on and what activities are most likely to trigger useful interaction. This information provides useful insights to design specific lab activities and evaluate the “effectiveness 1” of those activities.

The methodology itself could be further refined by using a smaller time interval or by using a flexible time interval. This would eliminate having to choose between two things that happen more or less simultaneously. Also, despite the near-real-time encoding of the data, it is still very time consuming and is therefore not suitable for a big quantitative study without significant resources. Any results obtained using this approach remain qualitative in nature, but provide nevertheless a valuable framework to compare different laboratories. As such, it can be used to analyze and modify other laboratories, not limited to electronics, or even other teaching approaches.

The video data themselves could also be analyzed focusing on other aspects, e.g., by looking at metacognitive statements made by students [48, 134, 135] or to study certain episodes in more depth to verify what specific problems students have with various aspects of the lab (measuring phase shift seems to be nontrivial, for example).

### 6.7.2 Black box lab

The black box approach seems to motivate the students to find out what is in the box, as could be observed during the videos, as well as by informal conversation with the teaching assistants and the students themselves. Motivation is an important condition for learning in constructivist learning theory. However, there are also more concrete indications that this approach helps students to learn conceptually from a laboratory session.

One of the main issues raised in several studies was that students often follow instructions as if the manual is a cookbook [10] and do not evaluate or discuss their measurements critically during the lab [10, 33, 43]. Especially the latter is important, since it is a missing link [33] to achieve one of the main aims of laboratory instruction in engineering: to integrate theory and practice[4, 23]. A related issue raised by Niedderer *et al.* [33] was that students generally spend too much time performing measurements. This was also clearly observed in the original laboratories and was related to the students’ unfamiliarity with the measurement equipment (at least at campuses 1 and 3).

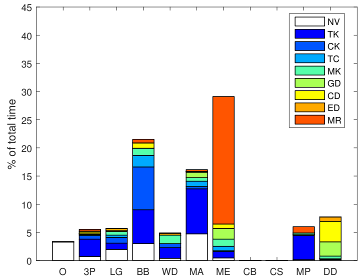
This greatly improved in the reformed labs by giving the students the chance to prepare with a simulator. The time spent on simply gathering measurements was further reduced by giving the students the Bode plot of the second circuit. This in turn gave them an opportunity to explicitly link their results back to their content knowledge, which was also indicated by our observation of the increase in data discussion (context DD) after this change was made. The use of the black box forced the students to decide the next frequency to measure by explicitly thinking about and discussing the previous measurement(s). This in turn required at least rough processing and analysis of those previous measurements. The students in the black box lab discussed their measurements with each other more often, not only after gathering all of them but also during the measurement process itself. We believe this to be at least partially thanks to the preparation, where students could practice measurement processing on a set of dummy measurements. In general, the black box laboratory increased the students' communication about content knowledge.

One aspect the students did not spend as much attention on in the new lab as in the original one was the phase shift between the input and output signals, despite having to do this in the preparation. A suggestion for future improvement is to require the students to determine the type of filter from one measurement alone (around the cutoff frequency), forcing them to use the phase and accurately measure its sign.

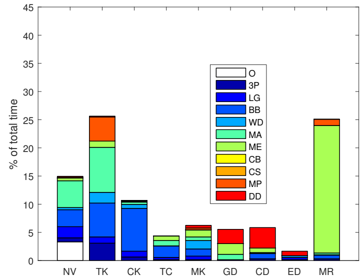
### 6.7.3 Suggestions for future research

The black box approach of the lab itself seems promising as an approach to force students to critically evaluate their measurements already during a laboratory session and could be extended to other labs, not limited to electronics. The idea of using reverse engineering in education is not new, but it is more used to teach engineering design methods rather than to teach content knowledge [136, 137]. It is hoped that this study will stimulate further investigations in this field.

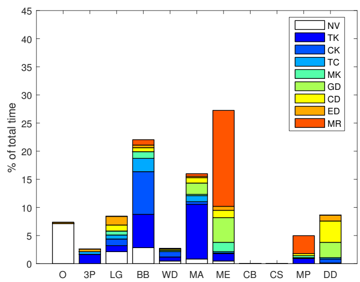
The idea of encoding both students' activities and verbalizations during lab work by using video recording is a very valuable tool in order to verify what activities trigger what kind of verbalization (and consequently, thinking). However, there is no way to verify the "effectiveness 2" of the laboratory using this method, so combining the approach used here with another tool to evaluate the learning outcome could greatly increase understanding of student learning. This would also allow to verify the claim made by Niedderer *et al.* that the verbalized knowledge during the laboratory is "an indicator for intended activities and *learning*" [33, 47].



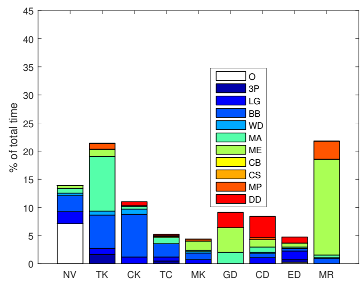

(a) Contexts for unprepared students at campus 1 with verbalization color-coded



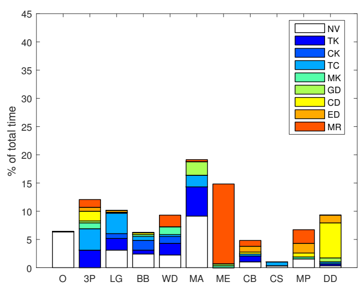

(b) Verbalizations for unprepared students at campus 1 with context color-coded



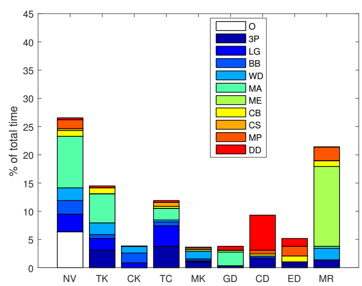

(c) Contexts for prepared students at campus 1 with verbalization color-coded




(d) Verbalizations for prepared students at campus 1 with context color-coded




(e) Contexts for students at campus 2 with verbalization color-coded




(f) Verbalizations for students at campus 2 with context color-coded

*Figure 6.6: Results of pilot labs. All percentages are the total of all pairs at the different campuses. Left are contexts in bins with verbalization marked by colors (6.6a, 6.6c and 6.6e), while right are verbalizations in bins with the contexts marked by colors (6.6b, 6.6d and 6.6f). The first and second row are respectively the unprepared (6.6a and 6.6b) and prepared (6.6c and 6.6d) students of campus 1, while the (prepared) students of campus 2 are on the third row (6.6e and 6.6f).*

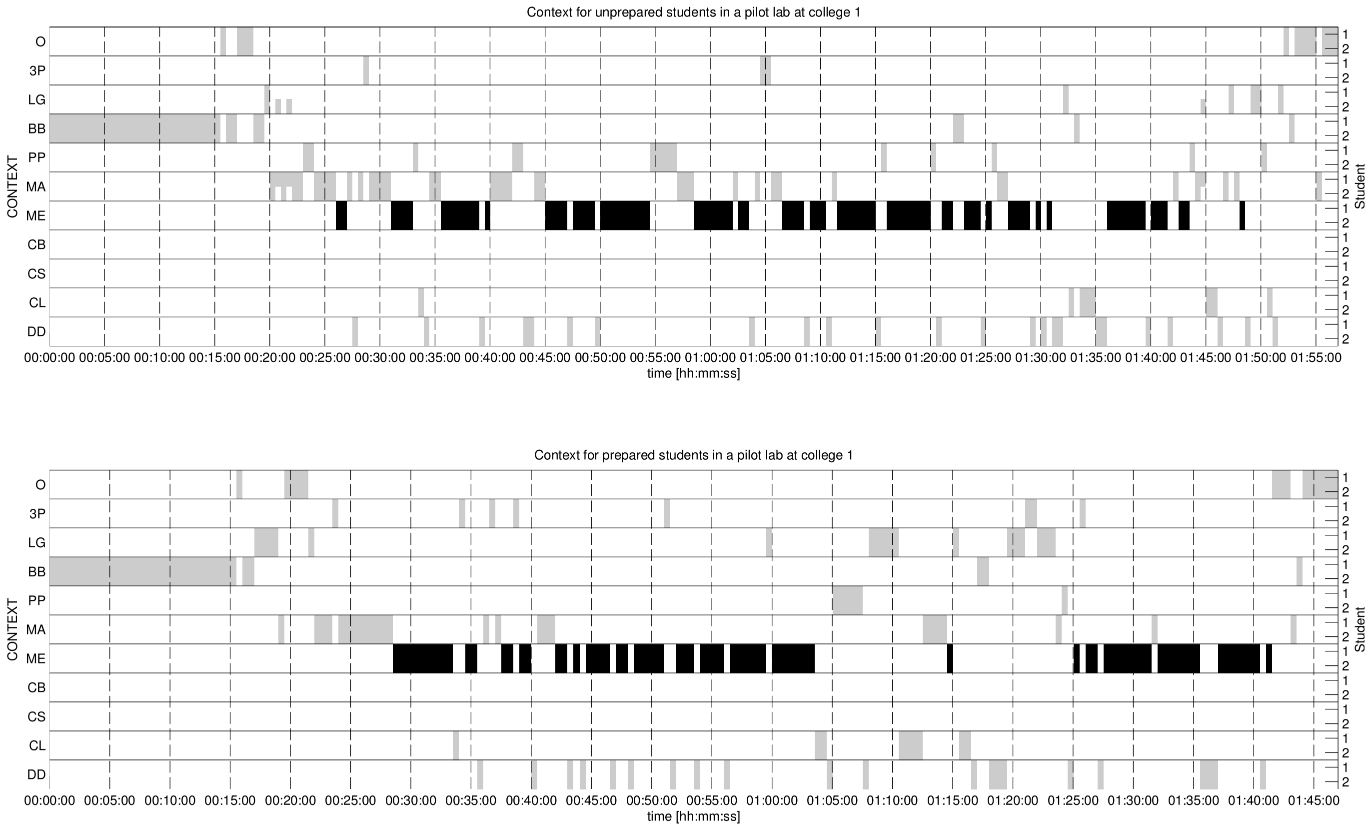
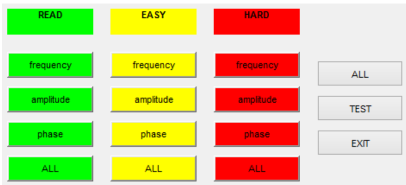
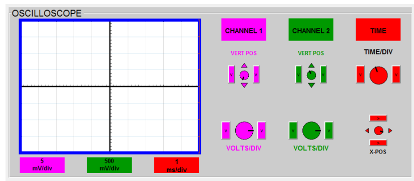


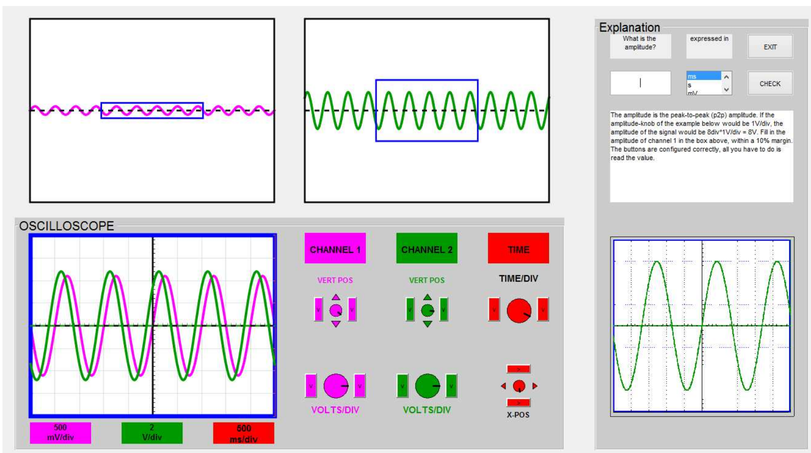

*Figure 6.7: Time lines for unprepared (top) and prepared (bottom) students in the pilot version of the new laboratory. Each line represents a context category and a block means that the activity represented by a context is done by the students. The highlighted line indicates the measurement context (ME). It is one more or less continuous block of measurements for the unprepared students, while there are two distinct clusters for the prepared students.*




(a)

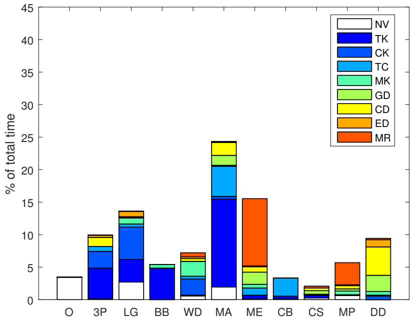



(b)

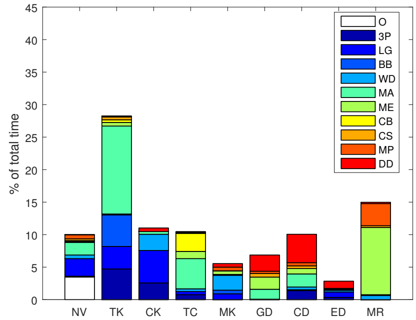



(c)

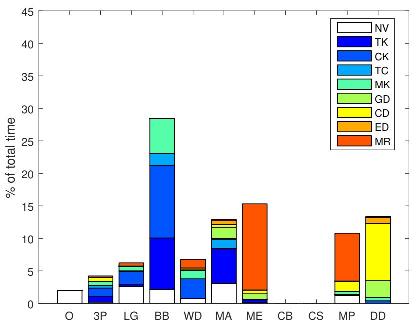
*Figure 6.8: Final version of the simulator. 6.8a In the first screen, the student can choose to practice reading a parameter at various levels of difficulty [well-configured oscilloscope, one setting (amplitude or time) misconfigured or fully misconfigured (both amplitude and time) scope] or to show the test to hand in at the beginning of the lab. 6.8c In the practice scope, there is an explanation about how to measure a parameter. The student can subsequently fill in the measurement value and choose the unit, after which the simulator will say whether it was correct or not. The test (6.8b) now only shows the oscilloscope screen with two signals that the student has to measure. The measurements are to be handed in at the beginning of the lab.*



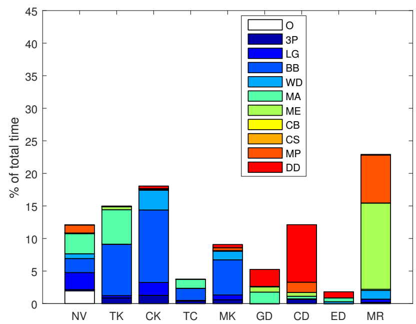

(a) Contexts for students at campus 1 with verbalization color-coded




(b) Verbalizations for students at campus 1 with context color-coded




(c) Contexts for students at campus 3 with verbalization color-coded




(d) Verbalizations for students at campus 3 with context color-coded

*Figure 6.9: Results of final labs. All percentages are the total of all pairs at the different campuses. Left are contexts with verbalization marked by colors (6.9a and 6.9c), while right are verbalizations with the contexts marked by colors (6.9b and 6.9d). The rows are campus 1 (6.9a and 6.9b) and campus 3 (6.9c and 6.9d), respectively.*

# Chapter 7

# Student reflections on labs

**Context**

As an extension of the interviews described in Chapter 3, 7 more students were interviewed a year later. The general course of the interviews was the same as described in Section 3.3 and took place at the same time of the semester. Again, the bulk of the interview was about the students' understanding of first order $RC$-filters. The results of this aspect were very similar to those of the year before and are briefly described in Section 7.2. Additionally, at the end of the interview, the students got the opportunity to talk about the structure and organisation of the lab. This chapter discusses that aspect of the interviews in more detail as they were an important basis for the changes made to the laboratory, which are discussed in more detail in Chapter 8.

## 7.1 Introduction

In the spring semester of the academic year 2011-2012, we interviewed 4 students of campus 2 about their knowledge of first-order $RC$-filters. All students were second (bachelor) year electronics engineering students who volunteered for the interviews. These interviews took place about a month after they had attended a lab session on the topic. The interviews were semi-structured and lasted about 30 minutes each. The interviews were both video- and audio-taped and notes that the students made on flipcharts were kept for later analysis. The students signed a written consent form prior to the interview. After the interviews, the recordings were used to critically assess the students' answers. The analysis not only focused on the correctness of their answers but also tried to gauge whether their reasoning was sound and reflected correct use of the underlying electronics concepts and principles. In case of incorrect answers, an effort was made to reconstruct the student's mental images that led him/her to this answer. The intent was to correctly reproduce the students' (possibly flawed) logic as a starting point for the development of instructional materials to help students overcome their incorrect conceptions.

The results of these interviews showed that students have various problems, including:

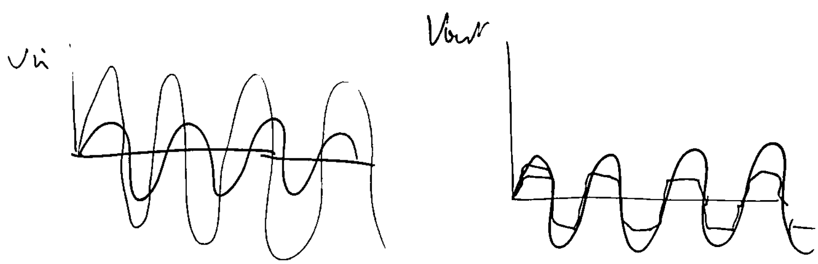
- Using basic circuit laws such as Ohm's law and Kirchhoff's laws;
- Drawing a circuit diagram of a filter;
- Knowing about and understanding phase shift between input and output voltages;
- Sketching and interpreting Bode plots.

More details about this aspect of the interviews can be found in Chapter 3.

The next year (spring 2013), 7 more students were interviewed in similar fashion about the same topic. Again, the students were in their second (bachelor) year of electronics. However, two of the students now came from campus 1, the other five were still from campus 2. The first 30 minutes or so of the interviews were conducted in the same way as the 2012 interviews: the students were probed about first order passive $RC$-filters and had flipcharts with markers available to sketch circuits, perform calculations, etc. The entire interview was recorded and the recordings were used for later analysis. However, after the initial part of the interviews, the students now had a chance to talk about the laboratory sessions themselves. This section of the interview lasted for 10-15 minutes and was also semi-structured. The questions in this part asked about what happened before (preparation), during and after the lab, as well as about their interaction with fellow students, teaching assistants and lecturers. Also this section of the interviews was audio recorded and analysed in much the same way as the technical section. The conclusions with respect to the laboratory sessions are discussed in sections 7.3 till 7.7, while a smaller discussion about the students' content knowledge is in section 7.2.

## 7.2 Content knowledge

The results of the interviews regarding student understanding of filters were very similar to the ones of the 4 interviews conducted in 2012: students struggled with basic circuit laws, did not know how to draw the circuit of a filter, forgot the phase shift between input and output and had problems using a Bode plot. One additional problem emerged when the last three students were also asked to draw a sine wave with a higher frequency on top of one drawn earlier. Only one of these three managed to do so correctly. Asking more students to draw a sine with a higher frequency was improvised by the interviewer because of the mistake Trevor[1] made when asked to sketch a signal with a higher frequency. He sketched a signal with a higher amplitude instead of a higher frequency, as shown in Fig. 7.1a. When asked how the signal would look after passing through his (perceived low-pass) filter, he sketched the signal of Fig. 7.1b, commenting it would "*become a sine function without the peaks actually.*" Another student, Sonny, said that there was no difference between the signal with a high and low frequency on his sketch, since "*you just turn the knobs* [on the oscilloscope] *until it looks the same again.*" When asked what actually happened when turning the knobs, he said he had no idea. Further probing to specify what the frequency then actually was, he said it was "*a property of the signal,*" but he did not know what it was exactly. He did know, however, that the output of his (low-pass) filter would have a lower amplitude when the signal would have a higher frequency. Both these comments point to issues with the understanding of the concept of frequency itself, unrelated to the context of filters. This led to the addition of an extra question to the conceptual test discussed in Chapters 4 and 5.




(a) (b)

*Figure 7.1: Trevor confused frequency and amplitude in Fig. 7.1a, also indicating that his (perceived low-pass) filter would 'shave off' the peaks and valleys of the sine wave, as shown in Fig. 7.1b.*

[1] as in Chapter 3, all names used are pseudonyms to respect the participants' privacy.

## 7.3 Connection to lectures

In verifying the goals of the laboratories, it became clear that a main goal of the laboratories was to help students gain a better understanding of the theory taught in lectures (see section 2.4.3). An important caveat there is that the theory covered during the labs should *not be new*. In other words, they should encounter it before and the labs should serve to consolidate and illustrate the theoretical knowledge, rather than to initiate it. However, this was not always the case in practice: all students report that some of the lab sessions took place before the subject of the session had been covered in lectures. At college 1, the teaching assistant of the lab would briefly cover the theory at the beginning of the laboratory, but this was not enough. At college 2, the students prepared for the labs and had to look up the background by themselves. All students felt this was a problem that should be addressed.

## 7.4 Preparation and report writing

At campus 1, the students did not have to prepare for the laboratories, while at campus 2 they had to make a preparation mainly consisting of theoretical calculations. The teaching assistant (TA) at campus 2 briefly checked at the beginning of the lab whether or not the students had prepared and whether there were any problems. All students reported that they made the preparation individually (so not together with their lab partners) and that they considered it useful to understand what "*was going on during the lab.*" At the first campus, the TA introduced the laboratory at the beginning of the lab, usually going over all questions in the labguide and pointing out possible difficulties.

At both campuses, the students had to hand in a lab report at the beginning of the next session, normally two weeks after the laboratory itself. All students at campus 2 reported that they *alternated* writing the reports within their group (pair). This meant that the students only wrote the reports for half of the topics. At campus 1, the students usually cooperated to write the report. At campus 2, all students found that the report took considerable effort and a lot of time to write. As reasons, they all cited the use of LaTeX, a way of text processing they were not used to prior to the lab. Additionally, they also used GNUplot to generate figures and were in general expected to work in Linux. Both of those were also new to them, which resulted in a time-consuming process to write the report. The students at campus 1 did not find that the report required a particularly big amount of time or effort.

At campus 2, the students indicated they received feedback to their report during the session after the one in which they submitted their report. This feedback was mainly on technical aspects of the writing (mistakes in figures, improper formatting and the like), one student (Simon) even saying he would "*learn more about LaTeX than about the content of the lab.*" Other feedback was about the conclusion, which was considered "*very important to* [the TA]" according to Scott, while "*he wouldn't shoot you for a measuring error.*"

## 7.5 Focus on measurements

During the laboratory sessions themselves, the students were mainly preoccupied with gathering measurement data. Students at campus 2 described it as follows:

SONNY: We sometimes build a circuit, then arrive at some measurement, but we have no idea whether it is right or not.

SIMON: Once we did like an entire table of measurements, but then [the TA] told us they were all wrong and we had to redo the whole set.

SCOTT: [during the lab] I'm not really thinking, that I do afterwards, at home. There is not enough time for that during the lab.

At campus 1, Trevor noted that when they were writing the report at home, they would "*sometimes notice that it* [=their data] *is all wrong, but then the lab is over already and you can't measure it again.*"

So in general, most of the time during the lab is spent performing measurements, which was also observed during the video-analysis (see Chapter 6, Section 6.4.3) and also surfaced in literature [33]. Students do not usually evaluate their measurements during the laboratory, sometimes finding out an "*entire table*" is wrong only after the laboratory. As Trevor (campus 1) noted, the "*deeper meaning*" only became clear *after* the laboratory, when they were working on their report. Simon and Sonny (campus 2) said they actually learned most when they had to "*draw the conclusions*" from their measurements and had to write down what they meant. Again, this took place *after* the laboratory itself, during the analysis of their measurement results.

At both campuses, students also had to make simulations of their circuit. However, this hardly ever happened during the lab session itself according to the students. Simon (campus 2) said they usually "*kept the simulations till the end of the lab. But we do not always manage to get there, so we keep them for* *at home.*" Scott (campus 2) on the other hand said that "*sometimes we do the simulation in advance*," although he also admitted it was mostly done at home after the lab. At campus 1, students clearly did not have enough time during the lab to process their measurements and end up doing their simulations at home.

## 7.6 Cooperation with other students and teaching assistants

Almost all students indicated they liked working in a pair during the labs. They said they helped each other and liked that if they did not know something, maybe their partner did or the other way around. Additionally, the students at campus 2 also made agreements to write their reports, as mentioned in Section 7.4. The students at campus 1 wrote the report together. Only one student (Scott) from campus 1 indicated he did not like working together with his colleague, mainly because the colleague seemed to be a weaker student and he had to spend too much time helping and coaching him instead of working together on the lab.

The interviewees indicated that cooperation with other student pairs was rather limited, although they sometimes helped each other "*for small things*" during the labs themselves, usually for technical issues. However, Sonny (campus 2) said they also sometimes "*compare measurements with other groups, although that's not really allowed.*" When asking Simon (campus 1) why there was so little cooperation between groups also after the lab, he said that "[the TA] *does not like it when we ask others, he prefers if we ask him.*" Several students at campus 2 referred to an online forum where they could help each other out after the lab, mainly with technical questions about LaTeX commands and other software-related issues. Trevor (campus 1) said that it happened they "*asked other students what they had*" after discovering the measurements that they made did not make sense. However, he also indicated that there was not much cooperation between different pairs in general.

All students were very positive about the TAs in charge of their laboratory sessions. They did not usually have to wait long for help and the TAs also regularly stopped at all pairs to ask how the lab was proceeding and help when needed. At campus 2, the TA also had office hours outside the lab time to answer questions about the report or the processing. Also at campus 1, the students were satisfied with the availability and help from their TAs. However, Trevor (campus 1) found that the explanation at the beginning was rather lengthy and did not like that everything was covered all at once, so "*when you had to use some equipment, you forgot what all the buttons were for.*" He also said that sometimes when they had a problem, the TA "*came and magically fixed it, but then you had no idea what happened and couldn't do it yourself.*"

## 7.7 Practical skills

Two of the students (one at each campus) specifically mentioned the wish to include more practical skills into the laboratory sessions, both citing soldering as an example. This is very much in line with the goals that students find important for a lab, but teachers do not appreciate as much (see Section 2.4.5). As a reason, one student talked about a project for a different course. He said that he needed certain practical skills there, but was thrown into the thick of things without a lot of experience.

Most of the students from campus 2 who struggled using linux, LaTeX and GNUplot also said that they eventually appreciated learning those skills at this point in their education, despite it being time-consuming and frustrating at times (as mentioned in Section 7.4). Again, this illustrates the interest in students to learn more practical skills during lab sessions.

## 7.8 Discussion

A surprising finding of the content section of the interviews was that several students did not have a good understanding of the concept of frequency itself. Further research will have to determine whether this is a widespread problem or it is limited to two students in the artificial setting of an interview.

When discussing the lab sessions themselves, the students revealed interesting thoughts. The sentiment that students want more practical skills in laboratories confirms the earlier findings about the expectations students have about laboratories discussed in Section 2.4.5. The revelation that students tend to alternate writing their lab reports is especially interesting since the reports serve as a basis for grading. Additionally, the writing of a lab report can also be a learning goal of itself in some cases, as is evident from Section 2.4.4.

The students also revealed several aspects of the lab that can serve as a basis for the improvement of the laboratories. The 5 students from the first campus had to prepare for their laboratory and indicated they benefited from this preparation. A second observation is the student feeling they spend a lot of time performing measurements, while the processing and interpretation is done at home. This can lead to frustration and incorrect data, hampering the students' learning. This suggests student learning may benefit from processing and especially interpretation of the data *during* the laboratory sessions themselves, when the TA is available for help and feedback.

The findings of these interviews will help to design a new laboratory session aimed at improving student learning of first order $RC$ filters.

# Chapter 8

# Design of a black box laboratory

**Context**

The video study described in Chapter 6 revealed that students do not focus often on concepts during the lab session. They spend a lot of time on dealing with equipment and measuring, but hardly talk about the underlying concepts. From the conceptual questionnaire discussed in Chapter 4 and especially 5, it is clear that the students enter the lab with little or no understanding of $RC$-filters or Bode plots. Also during the interviews described in Chapter 7, the students indicated they did not spend much time during the lab thinking about concepts, but instead learned most afterwards, while processing their measurements and writing a report at home. All findings suggest that students are overwhelmed by the laboratory because they encounter too many new tools and concepts at once. In order to trigger student thinking about the concepts underlying the lab experiment, a new lab was designed. This new laboratory consisted of both a preparation and an alternative lab assignment, using the same lab equipment. This chapter presents the new lab design in more detail than in the video paper of Chapter 6. Chapter 9 gives an overview of the results of the new laboratory on the questionnaire.

## 8.1 Introduction

In previous research, we uncovered various problems students have with understanding first order $RC$-filters by interviewing students (see Chapters 3 and 7) and administering a larger-scale questionnaire (Chapters 4 and 5). These problems persist despite laboratory instruction on the topic, with the aim of the instruction being to increase the students' conceptual understanding (see Chapter 2). Video analysis of the laboratories and further student interviews revealed several aspects of the laboratory sessions offering possibilities for improvement (see Chapter 6 and 7 respectively). While those improvements have been presented briefly in Sections 6.5.1 and 6.6.1, this chapter aims to give a more detailed overview of the redesigned laboratory. It starts with briefly introducing several relevant learning theories in Section 8.2.1 and reviewing the outcomes of the aforementioned studies in Section 8.2.2. Then, the goals and principles of the redesigned laboratory are presented in Section 8.2.3. A description of this laboratory follows, starting with the preparation in Section 8.3. The actual laboratory session is outlined in Section 8.4, with several modifications described in Section 8.5. A small discussion concludes the chapter in Section 8.6.

## 8.2 The need for a modified lab assignment

### 8.2.1 Learning theory background

According to constructivist theory, learning is an *active* process, in which the student engages with the subject matter to actively construct (new) mental models of certain phenomena [122]. According to a Piagetian point of view, a learner can either incorporate a new situation in his or her existing mental model of a certain phenomenon or adjust this pre-existing mental model to match both the new situation and previous experience. Learning is then the building and adjustment of these mental models. This implies that for learning to occur, a certain mental effort is required.

A learning theory that exemplifies this idea of the need for active mental engagement with the topic is so-called *learning by inquiry*. This is a way of learning that is especially important in the learning of sciences, related to the scientific method. In inquiry-based learning, the students perform a 'real' scientific experiment. This includes formulating a hypothesis to test, as well as a suitable test method to (dis)prove the hypothesis, gathering the evidence, and drawing conclusions from this evidence. The idea behind this method is that it forces the students to actively think about every step of the process. Learning by inquiry is sometimes used as a way to teach the scientific method to science students, but can also be used to teach conceptual knowledge. Banchi and Bell distinguish between four levels of inquiry [138]. The first is confirmation inquiry: the students receive a question from the teacher to which they already know the answer. In addition, the teacher also provides the method of investigation. The second is structured inquiry: the teacher provides an initial question and the procedure for the students to follow, but the students should arrive at a conclusion only based on their data. The third level is guided inquiry, where the teacher only provides a research question and the students decide on the method to answer it. The fourth and final level is open inquiry, in which the students formulate their own questions, design a method to evaluate it and answer their own question based on the results of their own procedures.

As mentioned, the idea behind this learning by inquiry is for students to think critically about the subject matter, as opposed to simply learning well-established facts (by heart). There is some research that suggests that students who only receive low-level inquiry instruction do not develop critical or scientific thinking very well [139–141]. A potential additional benefit of learning by inquiry is student motivation: Chu noticed that children were more motivated (and had better grades) when following an inquiry-based curriculum [142]. That being said, students can only benefit from this type of instruction if they have the necessary skills to conduct their research, such as being able to gather measurements, know how to process them as well as how to interpret the results.

Having a (flawed) pre-existing mental model for a certain phenomenon may however impede learning to a certain degree. Research has shown that it is harder to integrate new information properly when it contradicts pre-existing beliefs [88, 123, 124]. When interpreting evidence, for example measurement results, this can lead to what is known as confirmation bias [125]. This means that the results are interpreted in favour of a desired (or at least expected) outcome. It does not (necessarily) mean that data are falsified in any way, just that they are examined less critically than they should be.

A final principle that should be taken into account in addition to confirmation bias, is cognitive load. The human mind has a limited working memory available to consciously process information. This means that it is only possible to keep a limited number of pieces of information in mind while learning (or performing any kind of other mental activity for that matter). The amount of information that has to be kept in mind in order to perform a certain task, is called the *cognitive load* of that task [143]. When different aspects of this learning information also interact with each other, the amount of information that can be kept in the working memory is further reduced as each of the interactions also occupies a section of the working memory. However, it is possible to keep an interacting set of aspects in working memory as a single, abstract, entity (concept). This abstraction can be achieved by sufficient practise, after which, for example, a certain procedure requires little conscious effort any more and is processed virtually automatically. The single entity is referred to as a 'schema' by Van Merrienboer, Sweller and Paas [126]. In the context of a laboratory for example, the students who know how to configure their oscilloscope properly have a 'schema' of the oscilloscope and do not have to spend a lot of mental resources on setting up or handling the equipment. Students who do not have this experience on the other hand, spend considerable time and effort on setting it up properly and acquiring meaningful measurements with it.

An important aspect of designing any learning environment is therefore to reduce the cognitive load unrelated to the subject matter (the extraneous load) as much as possible. Then again, it is sometimes beneficial to deliberately increase the cognitive load in a situation to help the learner focus on certain aspects of the subject matter (germane cognitive load). The latter fosters active engagement with the topic, facilitating learning [126]. A counter-intuitive example of the extraneous load imposed by the type of assignment itself is when a set of knowns is given, and the student is asked the value of a specific parameter. This is very common in science and engineering teaching, for example when asking the students where a cannonball will land, given the initial velocity when it leaves the muzzle of the cannon. The issue with this type of questions is that the students not only have to keep their calculations in their working memory together with the initial conditions, but also the desired outcome and the path towards it.

A solution could be to work with goal-free problems, asking to calculate 'all possible values' when learning. In the example of the cannonball, the student could then calculate the maximum height, the time the cannonball was in the air, etc. This will lead to increased learning as the student is practising more than when only calculating one parameter, while at the same time the cognitive load is reduced: there is no need to keep the 'x' in mind, nor the entire path that leads to it. A second possible strategy is to use so-called *scaffolding*: initially, a student is asked to solve a task where a lot of support is provided. In subsequent iterations, more and more help is removed so more and more steps have to be taken by the student himself to successfully complete a task. The general idea is to make the first steps more familiar to the students before using them in a bigger framework [144, 145]. This in turn reduces the cognitive load needed for those first steps (by schema construction), freeing up active memory for a more difficult task. A third possibility is to use *variation theory* [146]. According to this learning theory, students benefit from a systematic variation in the teaching material. This results in contrasting two situations in which a parameter differs while the others are kept constant, probing the students to think about the effect of the change. This is a way to increase the germane cognitive load to direct the students' attention towards a certain aspect of the subject matter. This approach has been used in various contexts, including mechanics [53], electricity [50] and even opera studies [147].

### 8.2.2 Problems in the original laboratories

The analysis of the original laboratory revealed several problems. One of the main problems was that *students were using the equipment for the first time*. As a result, they were not proficient with it and struggled to *gather* measurements in the first place. This could be seen in the video analysis by the great amount of time spent measuring as well as the mistakes students made while measuring. Both aspects (big amount of time invested and many mistakes) are strong indications of a cognitive overload [143, 148–151]. The reason for this cognitive overload is most likely the combination of new pieces of apparatus (oscilloscope and function generator) with an unfamiliar way of looking at $RC$-circuits (as filters) and a novel way of presenting measurements (using a Bode plot). This resulted in little to no lab time spent discussing the measurement results and/or the underlying conceptual background of the laboratory topic, possible because there is too little time available to do so.

Another factor that probably contributed to the low amount of time spent critically evaluating measurements during the laboratory, was the *presence of an example set of measurements or pre-arranged table containing a set of given input frequencies in the lab manual*. This eliminated the need for students to think about previously gathered measurements when selecting the next frequency at which to perform a measurement. Although providing a set of frequencies reduces cognitive load, it is the *germane* cognitive load that is diminished: selecting a new frequency by themselves forces the students to actively think about the topic of the laboratory.

In addition, the students received a *known* resistor and capacitor to build their circuit and either chose whether to build a low- or high-pass filter or were told which one to build. At campus 2 and 3, this is even the same for all pairs. In other words, they knew the circuit in advance and could theoretically derive all its properties such as the cut-off frequency and the sign of the phase shift without the need to perform any measurements. Both aspects caused the students to suffer from a certain degree of confirmation bias, further preventing critical analysis of the measurement results and, as such, active mental engagement with the topic and thus learning [125]. This is evident not only from the lack of data discussion in the video study discussed in Section 6.4.3, but also from lab reports (for example the students who wrote there was "*small measuring error, as the phase should be -45°*" [not -48° as measured], ignoring the measurement of the amplitude which was -20dB) and the testimony of students during the interviews (see for example Trevor's statement that they'd only realise their measurements were wrong *after* the lab in Section 7.6). It made it easier for students to 'massage' their data and in general caused them to not spend much effort on a comparison with the simulation and/or theory. This closed nature of the lab assignment also further increased the cognitive load on the students in the sense that they had to keep the expected measurement outcome in mind in addition to all other aspects [126]. The very close-ended nature of the laboratory also means it is a level 1 type inquiry laboratory (they know the answer to the question and are told what method they have to use in rather great detail), which does not contribute to the development of students' critical thinking [139–141].

The problems mentioned above led to practical issues as well. The students only processed their measurements *after* the laboratory session and make the Bode plot and simulations at home, often even only done by one student of a pair as testified during the interviews (see Section 7.6). Sometimes they would realise only then that their measurements were wrong, without the possibility to gather new data.

The results on the questionnaire were disappointing: even after the lab, only a few students could answer questions about $RC$-filters correctly or recognised the circuits as filters (see Section 5). Another goal of the laboratory, to be able to construct and work with a Bode plot, is also only reached by a limited number of students who are able to construct a Bode plot given a set of (dummy) measurements (see Section 4.4.3).

### 8.2.3 Rationale behind the new laboratory

In general, the first aim of the adjusted laboratory is to improve the 'effectiveness 1', meaning that the activities of the students during the laboratory match the aims of the teachers *during* the lab session [29]. Ideally, we would like the new laboratory to address the problems discussed in Section 8.2.2, while aiming to achieve the same goals as in the original laboratory. So after the labs, the students should know:

- how to use lab equipment such as an oscilloscope and function generator;
- how to construct and use a Bode plot;
- the functioning of first order $RC$-filters.

An additional problem is that all these aspects are fundamental to the experimental study of $RC$-filters, as well as that of filters and even electronics in more general terms. This means simply leaving one or more aspects out is not possible. So to reduce cognitive overload due to the introduction of many new aspects at once, the students are asked to prepare for the new laboratory by practising oscilloscope reading as well as the construction of a Bode plot. The training of those skills in advance helps with schema building for those skills as mentioned earlier [126]. Having a more complete ‘schema’ for a skill (in this case oscilloscope reading and Bode plot construction) reduces the cognitive load while using this skill. In this specific case, performing a measurement or processing it can now be done more easily, with less need to check with the TA or a manual. In addition, performing measurements faster frees up time to discuss those measurements. The preparation is explained in more detail in Section 8.3.

During the actual laboratory, the circuit being measured will be *unknown* to the students, both to avoid confirmation bias and to reduce cognitive load further as the students do not have to (even cannot) keep the ‘correct’ answer in mind. To stimulate processing and discussion of measurements, there is no predetermined set of input frequencies given any more. To direct the students’ attention to the influence of the component values on the filter, variation theory is used by asking the students to measure two different circuits and determine what the difference between both is. To foster further discussion, some conceptual questions are added at the end of the laboratory manual. The eventual goal of the new laboratory is that the students are able to process and especially *discuss* their measurement results already *during* the laboratory session, both with each other and with their teaching assistant. The exact details and the lab manuals are described in Section 8.4.

To implement these changes, there are also several practical constraints to be taken into account. First of all, the new lab design should *keep the lab time* as it was in the original laboratories. Additionally, the new labs should *use the same equipment* as in the original laboratories, since that is the only one available to the students in the lab rooms. Finally, at the request of the teachers in whose course the research was done, the *reporting and simulation required* at the different campuses should be kept the same.

## 8.3 Design of the new laboratory: preparation

To reduce the cognitive overload the students suffer from during the laboratory itself, they are asked to prepare for the lab. This preparation included two aspects at campus 1 and 3: an oscilloscope simulation and an exercise in Bode plot construction. In addition to reducing the cognitive load imposed on the students during the laboratory session, making the students familiar with those two aspects is also necessary to make the more enquiry-based laboratory successful. At campus 2, preparation was part of the assignment already and was not changed with respect to the original lab. At this campus, the students also had prior experience with oscilloscope reading, making the simulation obsolete. After the pilot study at campus 1 and informal feedback of the students there, the preparation was optimised and used at campus 1 and 3. The assignment and simulation were made available online to the students a week prior to the laboratory and they were asked to bring a hard copy of their preparation with them to the session itself, where they were collected by the TA. Both aspects of the preparation, the Bode plot and oscilloscope simulation, are described in detail in Sections 8.3.1 and 8.3.2 below.

### 8.3.1 Bode plot

One of the concepts that the laboratory aims to teach the students is how to construct and interpret Bode plots. This is clear from the original lab manuals: all three clearly cite constructing Bode plots as a goal. However, the interviews (see Section 3.4.4) and the conceptual questionnaires (see Section 4.4.3) showed that students struggled with constructing Bode plots, often not even knowing that a Bode plot was a way of representing the output of a filter in relation to its input as a function of frequency. Those who actually sketched a Bode plot often sketched graphs corresponding to a first order $RC$-filter instead of one corresponding to the data in the table. In other words, they relied on memory instead of on proper understanding. A reason for this might be that the students hardly used the Bode plot during the lab: they did not process their measurements (by constructing a Bode plot) during the laboratories, but only did so at home after the lab session was over (see Sections 7.5 and 6.4.3). This resulted in less discussion and interpretation of the measurements in terms of content, inhibiting conceptual discussions during the lab session itself.
In order to get the students' feet wet in the domain of Bode plots, the first exercise of the preparation showed a table with dummy measurements and asked the students to plot the corresponding Bode plot, as shown in Fig. 8.1. To make sure the students did not just copy a plot from their course book or one they remembered from class, the measurements were of an attenuating

high-pass filter (HPF). This way, the students had to actively process them and could not rely on memory.

1. The table shows a series of measurements of a circuit. Calculate the gain in dB and sketch a possible corresponding Bode plot of these measurements on the back. Don't forget to label the axes properly and to include some numbers!

| $V_{in}$ [V] | $f_{in}$ [Hz] | $V_{out}$ [V] | $f_{out}$ [Hz] | $\varphi$ [°]* | $A$ [dB] |
|---|---|---|---|---|---|
| 10 | 1 | 0,010 | 1 | 90 | |
| 1 | 10 | 0,010 | 10 | 85 | |
| 1 | 100 | 0,071 | 100 | 45 | |
| 10 | 1000 | 1,000 | 1000 | 0 | |

**output with respect to input*

*Figure 8.1: Bode plot assignment of the preparation for the black box laboratory. Note that the 'measurements' are from an attenuating high-pass filter instead of from a 'normal' first-order RC-filter, making it impossible for the students to copy an example from their manual.*

### 8.3.2 Oscilloscope simulation

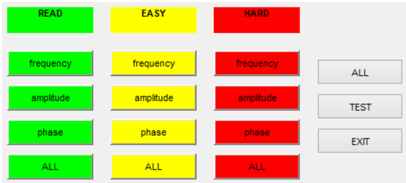
During the original laboratories, the students spent a lot of time setting up their equipment and even more performing measurements (see Section 6.4.2). This could be an indication of problems with the equipment, which was also seen in the interviews: many students mentioned that they struggled with the measurements and sometimes had to redo them (see Section 7.5). The video recordings of the laboratories also showed that this excessive amount of time spent performing measurements stemmed from problems using the oscilloscope. While the function generator was a new instrument as well, it proved to be less troublesome for the students. Problems with oscilloscope reading have also been mentioned by Bernhard [41]. The trouble students had with oscilloscopes was not only a matter of being confused by the myriad of buttons on an oscilloscope and subsequent failure to find the correct one, of plugging in cables in an incorrect port, or of triggering incorrectly, causing the signal to flicker and 'wander' on the screen. A far more important and fundamental problem was that students failed to adjust the signal using the amplitude and time division knobs, together with the horizontal and vertical adjustment knobs. These are the most essential tools on an oscilloscope, permitting to select a specific part of a signal, zoom in on it, align it properly with the grid on the scope, etc. A good example of the latter problem is student Sonny, who during the interviews exhibited a misconception about frequency (it being a 'property' of the signal, without knowing what property exactly). This was caused by him not understanding that the buttons served to zoom in and out as well as shift the signal. See Section 7.2 for the full discussion.

The second part of the preparation aims to help the students learn how to read an oscilloscope. This was done by designing a simulation in Matlab, a program available to the students at their campus. In addition to the simulator, they were also given a short explanation how to use the program itself as well as how to read signals on an oscilloscope. When starting the simulation, a user sees Fig. 8.2a, asking whether to practice or do the 'test' to be handed in at the start of the lab. The practice uses a scaffolding approach by providing the students with three levels of difficulty in reading a certain parameter (frequency, amplitude and phase). Choosing a parameter and difficulty, the student sees the 'learning unit' shown in Fig. 8.2c. It contains an explanation pane on the right, the oscilloscope screen with buttons and 'helping signals' on the left and an input section on the top right. In the first level of difficulty, labelled 'read', the 'buttons' on the oscilloscope are set correctly, so all the students have to do is read the chosen parameter. They can fill it in and select the corresponding unit in the top right of the screen, after which the simulation gives feedback telling them whether their answer and unit are correct or not. In the second step, labelled 'easy', either the amplitude settings (vertical shift and zoom) or time settings (horizontal shift and zoom) is set correctly, but the other one is off. This way, the students first have to adjust one set of knobs before they can read the signal. In a last step, labelled 'hard', both the amplitude and time settings are off, requiring the student to adjust both before being able to measure the signal properly. When clicking on the 'test' button, the student sees Fig. 8.2b, similar to the situation in the laboratory. They have to measure the amplitude and frequency of both signals on the screen, as well as the phase shift between both. Of course, both the time and amplitude settings are initially off in this case. At the beginning of the laboratory, they have to hand in their measurements together with a code generated by the simulation, so the TA can check their answer.

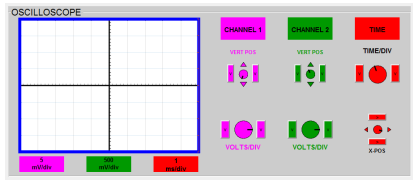
## 8.4 Design of the new laboratory: black box assignment

### 8.4.1 General idea of black box approach

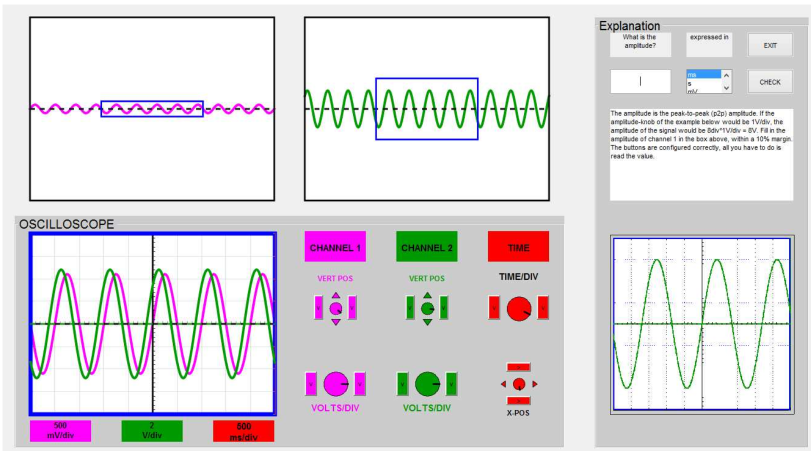
To avoid the confirmation bias students exhibited during the original laboratories, we decided to use black boxes for the circuits, an example of which is shown in




(a)




(b)




(c)

*Figure 8.2: Oscilloscope simulator. When starting it up, a student sees Fig. 8.2a, asking whether to practice or do the 'test' to be handed in at the start of the lab. When clicking on the latter, the student sees Fig. 8.2b, similar to the situation in the laboratory. Choosing a parameter and difficulty, the student sees the 'learning unit' shown in Fig. 8.2c. It contains an explanation pane on the right, the oscilloscope screen with buttons and 'helping signals' at the left and an input section on the top right. This is a repetition of Fig. 6.8.*

Fig. 8.3a. Such a (literally black) box has an unknown resistor and capacitor inside, configured as either a low- or high-pass filter. On the outside, only a switch and four connectors connectors are visible in addition to a sticker with an identification number for each box. All student pairs received a different box with different components and/or configuration. They only received a list of possible values for both the capacitor and the resistor but were not told what type of filter (LPF or HPF) was in their box. All they are told is that the circuit is a first order high- or low-pass $RC$-filter and that they have to determine the exact circuit, including component values.

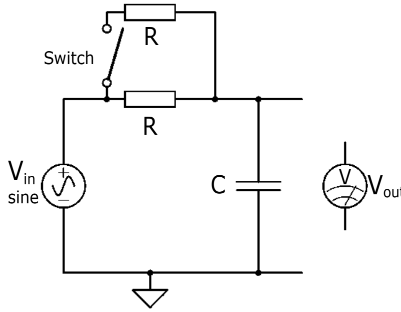
By performing similar measurements as in the original laboratory, they can determine the type of filter and its cut-off frequency. The former can even be done using only one measurement: if the output is leading the input signal (positive phase shift), the filter is a high-pass filter and vice versa. However, none of the students we observed arrived at a conclusion about their black box in this way. All determined their type of filter by performing a second measurement at a (sufficiently) different frequency. For example if it is a high-pass filter, one would expect the gain to be higher for a higher frequency. Once the type of filter is known, it is clear between which two terminals on the box the resistor is situated. Using a multimeter, one can then measure the value of $R$. The students can then find the cut-off frequency $f_c$ iteratively: at the frequency where the gain is -3dB and the phase shift is $|45°|$.The cut-off frequency depends on the product of $R$ and $C$. Since the value of $R$ and $f_c$ are known, $C$ is found by using the formula $f_c = 1/2\pi RC$. Knowing all component values as well as the type of filter, the entire configuration is now known. After flipping the switch, the same approach can be used. In this case, a change in resistor value makes it clear immediately what the switch does, while if the capacitor is changed, one can use the change in $f_c$ to determine the exact configuration.

This black-box laboratory is somewhere between level 2 and 3 type of inquiry, as the students do not know the answer to the question (they have to find out what is in the black box), and are less guided than in the original laboratory about the exact method to use (there is no predefined set of measurement points, nor an explicit indication that they should look for the cut-off frequency). In other words, the black-box laboratory has a higher level of inquiry, which should help the students to think more (critically) about the subject (in this case, filters).

Moreover, the use of a 'black box' eliminates the students' confirmation bias and lowers the cognitive load on the students by a reduced goal-specificity effect. As it is impossible to provide a set of frequencies at which to measure in advance, the students are now also forced to actively think about their measurements. In other words, the germane cognitive load is increased. In order to properly analyse the content of the black box, they also have to process the raw measurements and construct a Bode plot during the laboratory. This increases the 'training' with Bode plots, further enhancing the construction of this schema.

During the conceptual test, very few students recognised the $RC$-circuits as filters. By presenting the circuit explicitly as a two-port system in the black box, the students are encouraged to think about it as a filter with an in- and output.


(a)




(b)

*Figure 8.3: Black box and a (possible) circuit. The physical box is shown in Fig. 8.3a, where the black connectors are interconnected as ground level, while the red ones are the signal. The input is on the left, output on the right. The underlying circuit is shown next to it, in Fig. 8.3b. This is a repetition of Fig. 6.5.*

## 8.4.2 The switch on the 'black box'

To trigger more discussion about the content of the black box, a variation theory approach was used. According to this theory, a student learns by observing what happens when one parameter is changed, while the others are kept constant [146]. In the case of the black box circuit, this is done by changing the values of the resistor or capacitor. In practice, the boxes were equipped with a switch that would add either a resistor or a capacitor to the original circuit. This extra component would have the same value as the original component and would be added in series or parallel to the original component. An example of an LPF with a resistor added in parallel is shown in Fig. 8.3b. The result of adding a component means that its replacement value is either halved or doubled, causing the cut-off frequency to be doubled or halved, respectively. In the example of Fig. 8.3b an extra resistor is added in parallel. So the overall resistance in the circuit is halved, causing the cut-off frequency to double.

The task given to the students is to find out what happens when the switch is flipped: is there a resistor added or a capacitor? Is it added in series or in parallel? This can be done by determining the cut-off frequency as before and again calculating the value of the resistor and the capacitor. Once those are known, it is immediately clear which component has been added and in what configuration.

The goal of the entire exercise is to encourage student discussion about the influence of the component values on the circuit behaviour. Not only does it show them how the cut-off frequency changes, but they can also directly observe the effect of the change on the output voltage for the same input signal. At a given frequency, the output voltage will then be higher or lower than in the original circuit. In the example of Fig. 8.3b, the output voltage will be higher than in the original circuit for the same input signal.

### 8.4.3 Addition of Bode plot

At the third campus, there was very limited lab time (1h 30 min) available to the students. To allow them to find out what is in the box within the available time, we decided to change the second part of the assignment and gave the students the Bode plot of their box with the switch activated (with the extra component). This way, they only had to gather one set of measurements to determine what was in the box without the extra component. Instead of then gathering a second set of measurements, the students had to read the given Bode plot and compare it to their own measurements. This approach virtually halves the number of measurements required, allowing the students to finish the laboratory on time. This approach has the added benefit that the students are now forced to read and interpret the given Bode plot, again increasing germane cognitive load.

Since the students at this campus did not have to write any report about their lab session, we used this opportunity to add an answer sheet with an empty table for measurements and space to draw two circuit diagrams (meant for the circuit with and without the extra component). Each pair of students would get two such sheets, one they could keep and one to hand in at the end of the laboratory session. This also served as an extra stimulus to finish the lab on time and not postpone the processing till later.

When evaluating the pilot version of the black box laboratory at campus 1, we discovered that the students spent as much time performing measurements as they did in the original laboratories. However, this was because they actually performed a double set of measurements: one for the circuit without added component and one for the circuit with the extra component (see Fig. 8.4). This is discussed in Section 6.5 in more detail [120]. To limit the time spent on gathering measurements (twice), as well as to stimulate the students to process (and discuss) their measurements during the laboratory session itself, the approach used at campus 3 was also introduced at campus 1. So instead of performing a second set of measurements, the students received the Bode plot of the second circuit and had to hand in a copy of their measurements and circuit diagrams at the end of the lab session.

## 8.5 Design of the new laboratory: additional changes

The lab manual for the new laboratory had to be rewritten to take the preparation as well as the 'black box' approach into account. Some other, smaller changes were made to the manuals and are briefly discussed below.

### 8.5.1 Elimination of examples

One of the reasons why students at campus 1 did not discuss their measurements was that they had a ready table available to them with an example set of measurements as well as indications of important parameters. The students at campus 2 and 3 on the other hand, received a table where the frequencies, the most important parameter in the lab, were given in advance.

Giving the students a set of frequencies (input parameters) eliminates the need to decide the next frequency to measure. However, such a decision can only be made based on previous measurements. In other words, deciding about the input parameter can stimulate thinking about content knowledge, increasing the germane cognitive load.

In the lab guides for the new laboratories, the example table was removed at campus 1, while the list of input frequencies at the other campuses was removed as well. At those other two campuses, empty tables with prepared column headings were kept at the insistence of the TAs.

### 8.5.2 Conceptual questions

In addition to the general change of the lab, some conceptual questions were added to stimulate more discussion about filters. The first question asked what would happen to a signal with a DC-offset when using the AC-setting of an oscilloscope and why that actually happens. The aim of this question was for students to understand that the AC-setting on an oscilloscope (which eliminates the DC-offset) is essentially a high-pass filter. In a second question the students were asked how they would build different types of filters, such as

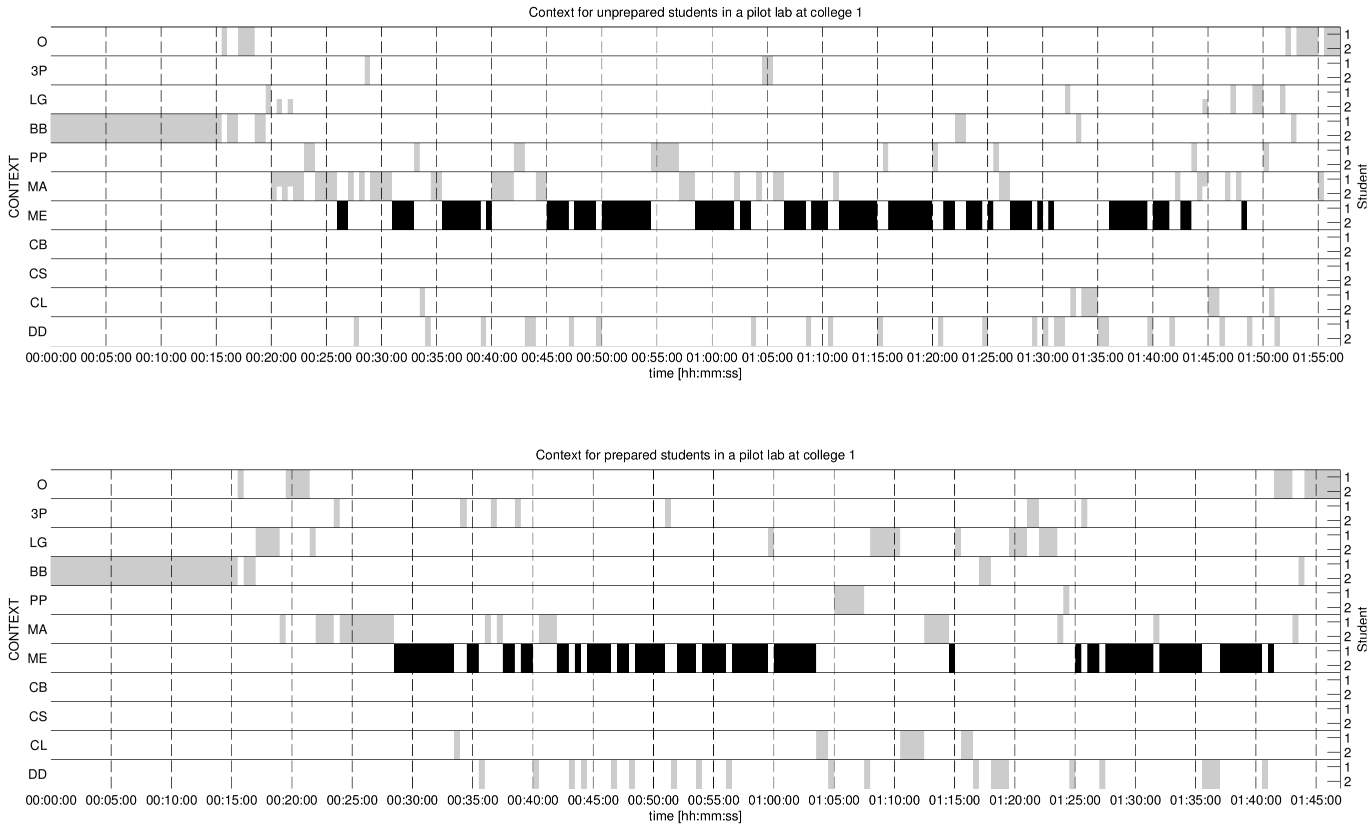



*Figure 8.4: Timelines for unprepared (top) and prepared (bottom) students in the pilot version of the new laboratory. The highlighted line indicates the measurement context (ME). It is one, more or less continuous, block of measurements in the unprepared labs, while there are two distinct clusters for the prepared students. The second cluster is when they measure the circuit again, but now after an extra component has been added. This is a repetition of Fig. 6.7.*

second order filters and band-pass filters. These can be constructed by using two first order $RC$-filters and cascading them. Not only is this question more 'forward engineering' oriented (as opposed to the reverse engineering lab), it also reinforces the presentation of the circuit as a filter as solving it is most easily done by cascading two first order $RC$-filters.

## 8.6 Conclusion

In general, this new laboratory design aims to address two major problems in the original laboratories: students being overwhelmed by the introduction of too many new aspects at once and suffering from a confirmation bias. Both problems led to the students spending a lot of time struggling with equipment and measuring while hardly any time was spent processing, simulating or discussing the result of measurements. In other words, they were cognitively overloaded and had little time or opportunity to actively think about the underlying concepts (and consequently, to learn). By preparing the students to use oscilloscopes and to process measurements before the laboratory, their cognitive load is reduced during the laboratory. As a result, they should spend less time on equipment set-up and measurement procedures, freeing time (and cognitive capacity) for interpretation and discussion of the measurements. The 'black box' approach of the new laboratory is meant to eliminate confirmation bias by the students and trigger a content-based discussion of the measurement results during the laboratory. The elimination of a measurement grid in the lab manuals and the obligation to hand in a conclusion at the end of the lab session have the same aim. The impact of these changes on the behaviour of the students during the laboratory itself was verified by using video-analysis and is discussed in Section 6.5.2 and 6.6.2. The results on the conceptual questionnaire will be discussed in Chapter 9.

# Chapter 9

# Learning outcomes of the black box laboratory

**Context**

As described in Chapter 6, the black box laboratories were analysed using video observation in the same way as the original laboratories. However, using only video analysis limits the evaluation of the new lab to gauging the students' activities and verbalisation *during* the laboratory, in other words the 'effectiveness 1' of the lab. To evaluate the learning outcomes after the lab session, or the 'effectiveness 2' of the laboratory, the students who took the black box laboratories answered the same conceptual questions that are described in Chapters 4 and 5. The test was taken at the same time as in the original laboratories, so both just before and about 1 month after the laboratory session itself. In this version of the questionnaire, there was an extra question added to verify how widespread the problems with the understanding of frequency were. This question is discussed in Section 9.2, together with the question about the signal with two frequencies. The results of the other questions are in Sections 9.3 till 9.6. For all of these, the questions themselves as well as their analysis is the same as in Chapters 4 and 5. A discussion of the results is in Section 9.7.

## 9.1 Introduction

As described in Chapters 4 and 5, we found that students still had conceptual difficulties with different aspects of $RC$-filters after they had worked through a lab session on the topic. The main difficulties were the following ones:

- **Direction of phase shift:** Although the concept of a phase shift is well understood, students struggle with the direction of this phase shift;
- **Constructing a Bode plot:** When given a set of measurements, most students did not manage to construct a good sketch of the corresponding Bode plot;
- **Sketching a signal with two frequencies:** A substantial number of students could not sketch a signal with two frequencies in the time domain;
- **Judging the impact of changing component values on a high-pass filter:** Students had difficulties sorting the output signals of a series of high-pass filters with the same (AC) input, but different components (doubled or halved resistor and/or capacitor values);
- **Distinguishing different input signals for a low-pass filter:** When shown a low-pass filter with AC and DC input signals, many students could not qualitatively predict how the output signals would relate to one another.

Based on these findings and on the results of the video-observation of Chapter 6, the lab session was redesigned as described in detail in Chapter 8. The effect on the course of the lab sessions themselves was analysed using the same video-analysis technique of Chapter 6, the results of which are described in Sections 6.5.2 and 6.6.2 of that chapter. To study the effect on student understanding of $RC$-filters after the lab, the same questionnaire used in Chapters 4 and 5 was administered as a pre- and post-test in the new laboratory. As some students showed problems with the concept of frequency in the interviews (see Section 7.2), an additional question was added. This question is discussed in Section 9.2.1. Additionally, the questions with the low- and high-pass filter were moved forward. This was done because 60 to 70% of students who answered those questions did not provide an explanation with their answer in the original version of the questionnaire. This could be because of the placement of the questions at the end of the questionnaire, as studies have shown participants spend less time and effort on their answer [118] or are more likely not to answer to a question at the end of a quesionnaire [119]. The exact order of all questions on all versions of the questionnaire is in Table 9.1.

*Table 9.1: Order of questions in all runs of the conceptual test*

| Question | 1 frequency | | 2 frequencies | | phase | | LPF | | Bode | | HPF | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Timing | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| Original campus 1 | / | / | 3 | 1 | 4 | 2 | 1 | 3 | 2 | 4 | 5 | 5 |
| Original campus 2 | / | / | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 5 | 5 |
| Original campus 3 | 1 | 1 | 4 | 4 | 2 | 2 | 3 | 3 | 5 | 5 | 6 | 6 |
| Unprepared pilot campus 1 | 1 | 5 | / | 3 | 2 | 6 | 3 | 2 | 4 | 4 | 5 | 1 |
| Prepared pilot campus 1 | 1 | 5 | / | 3 | 2 | 6 | 3 | 2 | 4 | 4 | 5 | 1 |
| Pilot campus 2 | 5 | 5 | 3 | 3 | 6 | 6 | 2 | 2 | 4 | 4 | 1 | 1 |
| Final campus 1 | 5 | 5 | 3 | 3 | 6 | 6 | 2 | 2 | 4 | 4 | 1 | 1 |
| Final campus 3 | 5 | 5 | 3 | 3 | 6 | 6 | 2 | 2 | 4 | 4 | 1 | 1 |

*Table 9.2: Number of participating students in all runs of the conceptual test*

| Campus | # students Pre | Post |
|---|---|---|
| Original campus 1 | 87 | 74 |
| Original campus 2 | 13 | 11 |
| Original campus 3 | 81 | 71 |
| Unprepared pilot campus 1 | 16 | 37 |
| Prepared pilot campus 1 | 21 | 20 |
| Pilot campus 2 | 9 | 9 |
| Final campus 1 | 84 | 79 |
| Final campus 3 | 93 | 87 |

## 9.2 Understanding of frequency

### 9.2.1 Single frequency signal

As mentioned in the introduction, one question was added to the questionnaire based on the problems some students had with frequency during the last interviews (see Section 7.2). In this question, the graph of a simple sine wave was given in the time domain and students were asked what the frequency of the signal was. Then, they were asked to sketch a signal on top of the original signal that had either double or half (depending on the questionnaire) the frequency of the given one. The exact formulation is in Fig. 9.1.

The only campus in which this question was asked in the original laboratory was campus 3 as this was the only campus where the original lab took place after the second set of interviews. The question was asked at all campuses both before and after the pilot version of the black box lab as well as before and after the final implementation of that lab.

As with the other questions, the students' answers were assigned to categories that emerged bottom-up from the answers themselves. In addition to the 'blank' category, the results for reading the frequency of the signal were classified as either correct or incorrect. The main reason not to elaborate on different categories was simply that very few students answered this part of the question incorrectly. In the part where the participants had to sketch a signal with either a higher or lower frequency, 4 answer categories emerged:

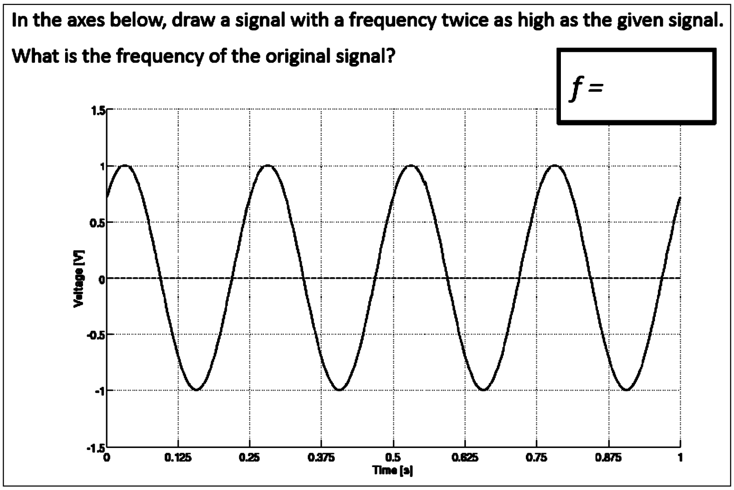



*Figure 9.1: Single frequency question*

- **Correct** A sine wave with (more or less) the correct frequency;
- **Opposite** Answers that showed a signal with half the frequency when double was asked or vice versa;
- **Other** Students who gave an (incorrect) answer not belonging to the category above;
- **Blank** Students who did not answer this (part of the) question.

When reading the frequency of the signal, most students did very well. In general, the most common mistake was to answer with a frequency twice as high as the one of the sketched signal. A possible explanation for this is that students think the period of the signal is only one 'lobe' of the sine wave. The prevalence of the different answer possibilities (correct, incorrect or blank) is in Table 9.3.

When it comes to drawing a signal with a higher or lower frequency, the students did not have any problems overall at any of the campuses, with the students at campus 3 performing best of all. The results are in Table 9.4.

So overall, there were no major problems with student understanding of how to read the frequency of a sine wave: 70% of students do so correctly regardless of campus or lab type. Sketching a signal with a higher or lower frequency is even less problematic. So probably the students in the interviews were either exceptions or their mistakes were caused by the unfamiliar setting of the interview.

*Table 9.3: Results of reading a single frequency for all labs (original, pilot and final black box) at all campuses*

| | # students | | Correct (%) | | Incorrect (%) | | Blank (%) | |
|---|---|---|---|---|---|---|---|---|
| Campus | Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| $3^{o}$ | 81 | 71 | 96 | 80 | 4 | 18 | 0 | 1 |
| $1^{p\ *}$ | 16 | 37 | 81 | 51 | 19 | 41 | 0 | 8 |
| $1^{p}$ | 21 | 20 | 67 | 65 | 33 | 30 | 0 | 5 |
| $2^{p}$ | 9 | 9 | 67 | 100 | 33 | 0 | 0 | 0 |
| $1^{f}$ | 84 | 79 | 63 | 68 | 19 | 27 | 18 | 5 |
| $3^{f}$ | 93 | 87 | 86 | 93 | 10 | 7 | 4 | 0 |

$^{o}$ Original laboratory
$^{p}$ Pilot version of black box laboratory
$^{f}$ Final version of black box laboratory
$^{*}$ Unprepared students

*Table 9.4: Results of sketching a signal with a doubled or halved frequency on top of a given signal for all labs (original, pilot and final black box) at all campuses*

| | # students | | Correct (%) | | Opposite (%) | | Other (%) | | Blank (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Campus | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| $3^{o}$ | 81 | 71 | 85 | 87 | 2 | 0 | 0 | 3 | 12 | 10 |
| $1^{p\ *}$ | 16 | 37 | 94 | 76 | 0 | 14 | 0 | 0 | 6 | 11 |
| $1^{p}$ | 21 | 20 | 86 | 70 | 10 | 20 | 0 | 5 | 5 | 5 |
| $2^{p}$ | 9 | 9 | 67 | 89 | 11 | 0 | 11 | 0 | 11 | 11 |
| $1^{f}$ | 84 | 79 | 52 | 86 | 21 | 9 | 4 | 4 | 23 | 1 |
| $3^{f}$ | 93 | 87 | 91 | 92 | 2 | 0 | 0 | 0 | 6 | 8 |

$^{o}$ Original laboratory
$^{p}$ Pilot version of black box laboratory
$^{f}$ Final version of black box laboratory
$^{*}$ Unprepared students

### 9.2.2 Signal with two frequencies

This question is question III of the example questionnaire in Appendix B and is shown in Fig. 9.2. It asked the students to sketch a signal with two frequencies in the time domain.

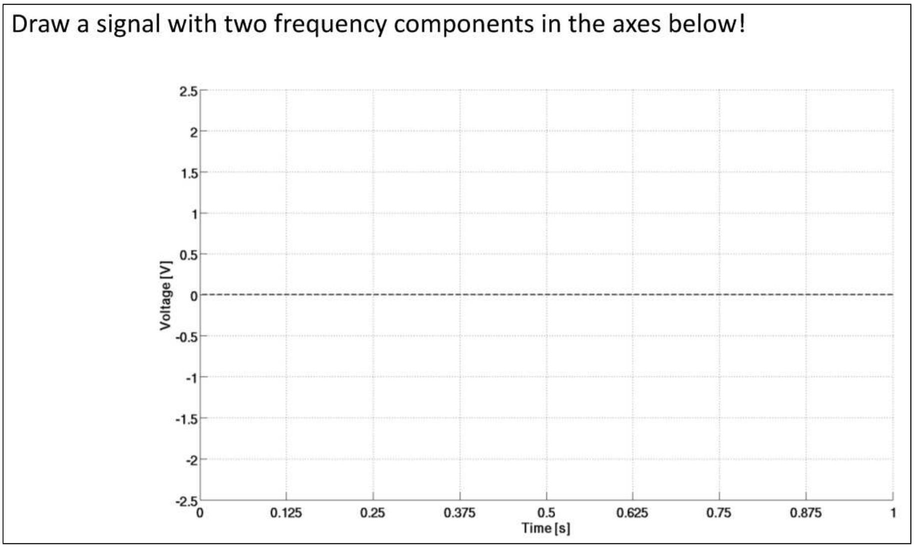



*Figure 9.2: Signal with two frequencies question*

The students' answers were classified into several categories. These categories were built bottom-up from the student responses themselves and are discussed at length in Section 4.4.2. Examples of all categories are in Figs. 9.3 and 9.4 for correct and incorrect answers, respectively. Because of their low prevalence and to simplify the analysis, the categories 'offset', 'f-domain' and 'AM' used in Chapter 4 are combined in the 'Other' category (correct answers). Similarly, the 'Bode plot' category was added to the 'Other' category for the incorrect answers.

The results of all laboratories (original, black box pilot and final black box) are in Tables 9.5 and 9.6, again for the correct and incorrect answers, respectively. This question was omitted in the pre-lab test of the pilot laboratory at campus 1 at the request of the TAs to reduce the length of the test. The question was used again in the post-test of that laboratory.

In the original laboratory, about half the students answered this question correctly after the laboratory. Before the lab, the students at campus 1

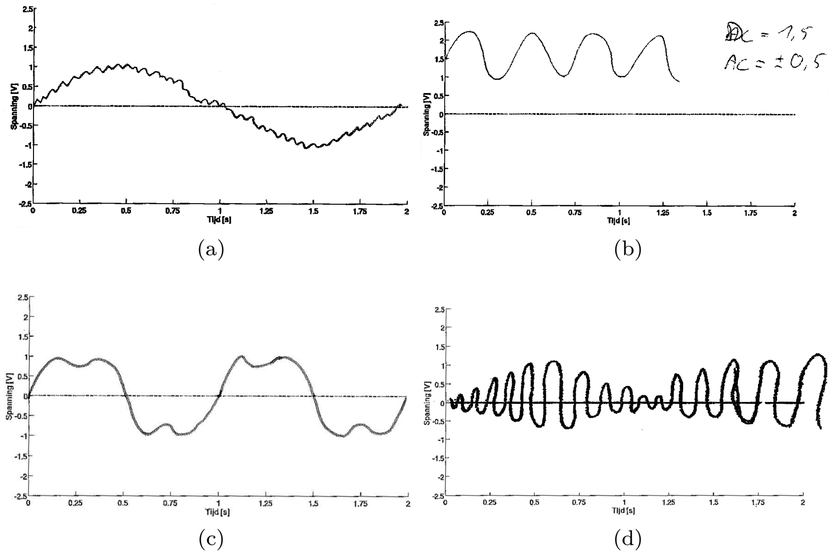



*Figure 9.3: Examples of correct student answers to the double frequencies question. The Dutch labels on the axis mean "Time [s]" and "Voltage [V]" for the horizontal and vertical axis respectively. 9.3a is a noisy sine wave. 9.3c is a manually added signal. 9.3b has a DC-offset, with the student explicitly indicating the DC-offset and 9.3d is an AM-like signal. Both of the latter are examples of the 'Other' category. This is a repetition of Fig. 4.4.*

performed a lot worse. Most of the correct answers fell into the so-called 'manual' category, indicating the students did not have a ready example of a signal with two frequencies in mind but instead constructed it 'on the spot' by manually adding two sine waves with slightly different frequencies. The incorrect answers were most often two overlapping signals.

After the pilot version of the new laboratory, the students at campus 1 did a lot worse than after the original laboratories: many students left this question blank (almost 40 %). An explanation could be a lack of time to answer this question as it was moved to the end of the questionnaire for these labs. However, the prepared students performed better than their unprepared colleagues. At campus 2, the students did better after the pilot version of the black box laboratory than their colleagues the year before after following the original laboratory, despite performing more or less similar before the start of the laboratory. Then again, there were very few students at this campus, so the results should be interpreted with caution.

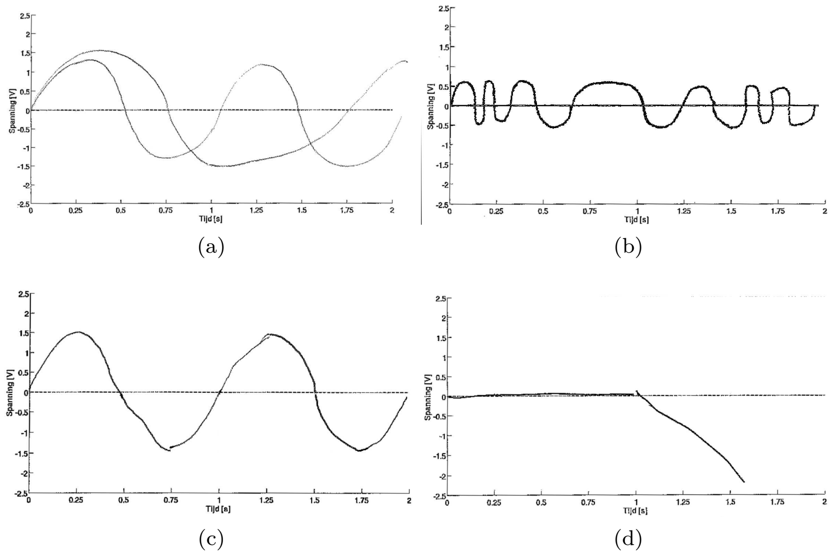



Figure 9.4: *Examples of incorrect student answers to the double frequency question. The Dutch labels on the axis mean "Time [s]" and "Voltage [V]" for the horizontal and vertical axis respectively. 9.4a are overlapping signals. 9.4b is an FM-like signal. 9.4c is a single-frequency signal. 9.4d is a Bode-plot, an example of the 'Other' category. This is a repetition of Fig. 4.5.*

When taking the final version of the black box laboratory, the students at campus 1 performed worse than the students during the original laboratories, both before and after the laboratory session. The biggest change was the increase in the number of blanks for students who attended the black box laboratory, which may again indicate the result is due to the position of the question in the overall questionnaire (at the end). Additionally, the fraction of students sketching two manually added signals was lower in the black box laboratory, while there were slightly more students who used a signal with only 1 frequency or two overlapping signals. Much the same happened at campus 3, where the number of blank answers was even higher. The main difference between the different labs at this campus was the lower fraction of students in the black box laboratory who used the 'noisy sine' of Fig. 9.3a.

*Table 9.5: Correct results of sketching a signal with double frequency for all labs (original, pilot and final black box) at all campuses. Please note that the categories 'offset', 'f-domain' and 'AM' used in Chapter 4 are combined in the 'Other' category.*

| | # students | | Noise (%) | | Manual (%) | | Other (%) | | **Total (%)** | |
|---|---|---|---|---|---|---|---|---|---|---|
| Campus | Pre | Post | Pre | Post | Pre | Post | Pre | Post | **Pre** | **Post** |
| 1 $^{o}$ | 87 | 74 | 7 | 31 | 17 | 24 | 2 | 8 | **26** | **64** |
| 2 $^{o}$ | 13 | 11 | 0 | 0 | 38 | 9 | 8 | 27 | **46** | **36** |
| 3 $^{o}$ | 81 | 71 | 11 | 14 | 53 | 55 | 3 | 13 | **68** | **82** |
| 1 $^{p}$ $^{*}$ | 16 | 37 | / | 3 | / | 16 | / | 13 | **/** | **32** |
| 1 $^{p}$ | 21 | 20 | / | 20 | / | 25 | / | 5 | **/** | **50** |
| 2 $^{p}$ | 9 | 9 | 0 | 0 | 44 | 78 | 0 | 0 | **44** | **78** |
| 1 $^{f}$ | 84 | 79 | 8 | 23 | 7 | 11 | 2 | 1 | **18** | **38** |
| 3 $^{f}$ | 93 | 87 | 0 | 1 | 33 | 62 | 3 | 1 | **37** | **64** |

$^{o}$ Original laboratory
$^{p}$ Pilot version of black box laboratory
$^{f}$ Final version of black box laboratory
$^{*}$ Unprepared students

### 9.2.3 Discussion

Overall, the students did not seem to have big problems reading the frequency of a given sine wave. The final black box laboratories showed a positive influence, both when comparing the original lab with the new one at campus 1 (the students performed worse in the pre-test, but did better after the lab) and when comparing the pilot to the final version (at campus 1).
There were more problems when students were asked about a signal with two frequency components however. The black box laboratory and/or its preparation did not have a positive influence on the students' performance on this question, on the contrary. While this could be due to the position of the question in the overall questionnaire (at the end, causing more blanks [118, 119]), the exact reason is unclear. The new laboratory did not emphasise signals with multiple frequencies any more or less than the original laboratories, except at campus 3, where the signals used in the original laboratories had a DC-offset. Although there was a decrease in the number of students using a DC-offset to answer the question in the questionnaire, the decrease in the number of students who used a noisy sine wave, for example, was much bigger.

## 9.3 Understanding of phase

To study student understanding of phase shifts, one question in the questionnaire asked to sketch a signal that was leading (or lagging, depending on the

*Table 9.6: Incorrect results of sketching a signal with double frequency for all labs (original, pilot and final black box) at all campuses. The total percentage is calculated without taking students into account who left this questions blank.*

| | # students | | FM (%) | | Sine (%) | | Overlap (%) | | Other (%) | | Blank (%) | | **Total (%)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Campus | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post | **Pre** | **Post** |
| 1 $^{o}$ | 87 | 74 | 8 | 5 | 11 | 5 | 13 | 4 | 14 | 6 | 28 | 15 | **46** | **22** |
| 2 $^{o}$ | 13 | 11 | 0 | 9 | 15 | 0 | 8 | 36 | 8 | 9 | 23 | 9 | **31** | **55** |
| 3 $^{o}$ | 81 | 71 | 11 | 7 | 1 | 0 | 6 | 1 | 9 | 10 | 4 | 0 | **28** | **18** |
| 1 $^{p\ *}$ | 16 | 37 | / | 5 | / | 16 | / | 3 | / | 5 | / | 38 | **/** | **30** |
| 1 $^{p}$ | 21 | 20 | / | 5 | / | 0 | / | 15 | / | 0 | / | 30 | **/** | **20** |
| 2 $^{p}$ | 9 | 9 | 0 | 0 | 0 | 0 | 11 | 11 | 0 | 11 | 44 | 0 | **11** | **22** |
| 1 $^{f}$ | 84 | 79 | 6 | 5 | 7 | 13 | 17 | 14 | 15 | 10 | 38 | 23 | **44** | **42** |
| 3 $^{f}$ | 93 | 87 | 12 | 8 | 3 | 5 | 10 | 7 | 18 | 5 | 20 | 11 | **43** | **24** |

$^{o}$ Original laboratory
$^{p}$ Pilot version of black box laboratory
$^{f}$ Final version of black box laboratory
$^{*}$ Unprepared students

questionnaire) a given sine wave by 90°. The exact formulation of the question is in Fig. 9.5 below.

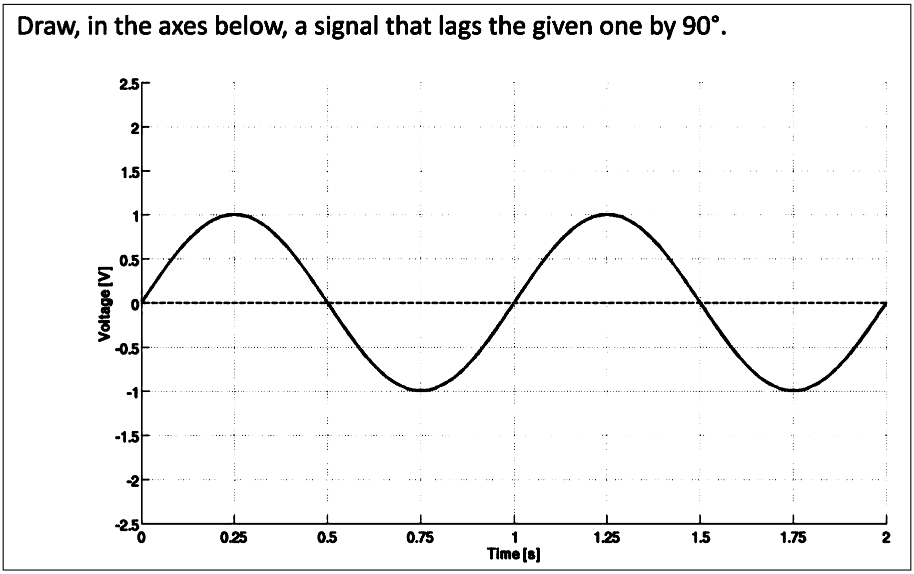



*Figure 9.5: Phase shift question*

## 9.3.1 Phase shift as such

The answers were categorised according to the phase shift the students sketched as discussed in Section 4.4.1. The different categories were a correct answer, an answer that was |90°| but with the wrong sign (i.e. sketching -90° when leading was asked or vice versa) or 180°. In addition to those options, there were some answers that did not fit into any category. A last group did not answer the question. An overview of all answers at all campuses and across all laboratory settings is in Table 9.7.

During the original laboratory, the majority of the students gave a correct answer to this question. Those who did not usually still showed a signal that was shifted 90°, but in the wrong direction. So overall, students knew very well what a phase shift was and what its size was, but had problems with the *direction.*

The students who performed the pilot version of the black box laboratory performed very similarly: while knowing very well what a 90° phase shift is, they still had problems with the direction. There was however no significant difference in the number of students who answered this question correctly across the different laboratory types, nor was there between students before and after the laboratory. The only differences that could be found was when the direction of the phase shift is not taken into account. Even so, this was solely because of the students after the original lab at campus 1. They knew significantly better than they did before the laboratory what a 90° phase shift is. They also knew this significantly better than their colleagues who were not prepared for the pilot version of the black box laboratory and those who took the final version of the black box laboratory.

### 9.3.2 Shift in time

During the original laboratory, some students sketched their phase shifted signal starting at a different point in time, see Fig. 9.6 for an example. An overview of how many students did so and whether it was when they sketched a positive or negative phase shift is in Table 9.8. In the original laboratory, this happened most often when the student sketched a lagging signal, regardless of what was asked in the question. In the black box laboratory, the pattern was the same: students were more likely to use this 'time shift' approach when sketching a lagging signal regardless of the question. At campus 1, the number of students who did this was a lot higher than in the original laboratory. When asked to draw a lagging signal (in the pre-test at the pilot labs and the post-test of the final ones), half of the students did this, at least when they were prepared. At campus 2 and 3, there was not much difference between the original and the black box labs.

*Table 9.7: Results of phase shift question at all laboratories (original, pilot and final black box) at all campuses.*

| | # students | | Correct (%) | | Sign (%) | | 180°(%) | | Other (%) | | Blank (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Campus | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post |
| 1 $^o$ | 87 | 74 | 66 | 69 | 20 | 27 | 14 | 4 | 1 | 0 | 0 | 0 |
| 2 $^o$ | 13 | 11 | 38 | 64 | 46 | 36 | 15 | 0 | 0 | 0 | 0 | 0 |
| 3 $^o$ | 81 | 71 | 73 | 83 | 15 | 3 | 9 | 13 | 4 | 1 | 0 | 0 |
| 1 $^{p\ *}$ | 16 | 37 | 75 | 59 | 13 | 22 | 13 | 11 | 0 | 8 | 0 | 0 |
| 1 $^p$ | 21 | 20 | 67 | 80 | 19 | 10 | 14 | 0 | 0 | 5 | 0 | 5 |
| 2 $^p$ | 9 | 9 | 44 | 33 | 44 | 22 | 11 | 33 | 0 | 11 | 0 | 0 |
| 1 $^f$ | 84 | 79 | 62 | 56 | 15 | 24 | 8 | 11 | 0 | 5 | 14 | 4 |
| 3 $^f$ | 93 | 87 | 74 | 85 | 20 | 9 | 4 | 5 | 0 | 1 | 1 | 0 |

$^o$ Original laboratory
$^p$ Pilot version of black box laboratory
$^f$ Final version of black box laboratory
$^*$ Unprepared students

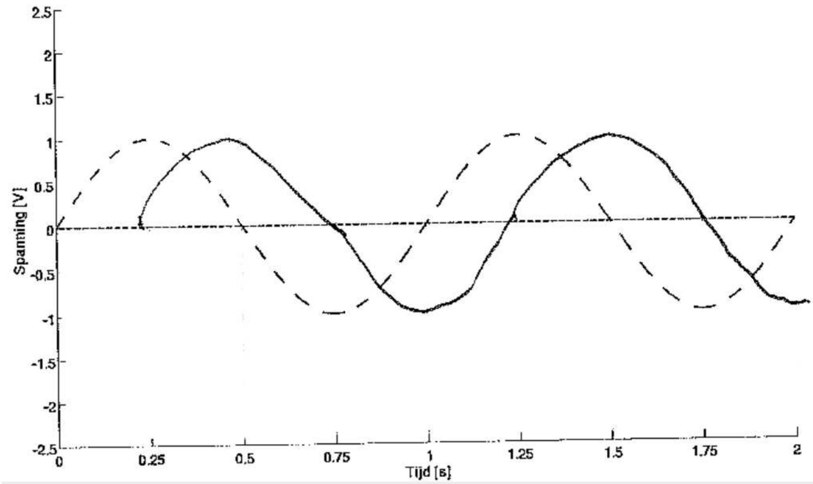



*Figure 9.6: Time shifted signal, starting later than the given signal (dashed). This is a repetition of Fig. 4.2.*

*Table 9.8: Students using a 'time shift' when asked about a phase shift. The numbers shown are # with timeshift/total #.*

| | Asked | | +90° drawn | | -90° drawn | |
|---|---|---|---|---|---|---|
| Campus | Pre | Post | Pre | Post | Pre | Post |
| 1 $^{o}$ | +90° | -90° | 2/57 | 1/20 | 6/17 | 10/51 |
| 2 $^{o}$ | -90° | +90° | 0/6 | 0/7 | 2/5 | 0/4 |
| 3 $^{o}$ | +90° | -90° | 1/59 | 2/2 | 3/12 | 0/59 |
| 1 $^{p\ *}$ | +90° | -90° | 0/12 | 1/8 | 1/2 | 7/22 |
| 1 $^{p}$ | +90° | -90° | 0/14 | 0/2 | 1/4 | 10/16 |
| 2 $^{p}$ | -90° | +90° | 0/4 | 0/3 | 1/4 | 0/2 |
| 1 $^{f}$ | -90° | +90° | 0/13 | 1/44 | 32/52 | 11/19 |
| 3 $^{f}$ | -90° | +90° | 1/19 | 4/74 | 9/69 | 4/8 |

$^{o}$ Original laboratory
$^{p}$ Pilot version of black box laboratory
$^{f}$ Final version of black box laboratory
$^{*}$ Unprepared students

### 9.3.3 Discussion

The new lab did not have a positive influence on students' understanding of a phase shift. At one campus, they even performed worse when only taking the absolute value of the phase shift into account. However, they were still well aware of what a phase shift is (a shift in the time-domain), much like in the original laboratories. The reason why they had more problems in the new laboratory could be because of a lack of emphasis on measuring the phase shift during the laboratory itself: during the original laboratory, the students were explicitly asked to measure both the phase and the amplitude, while there was less emphasis or need to measure the phase in the 'black box' laboratory.

There was also an increase in the number of students who explicitly moved the signal in the time domain in the new laboratory, especially at campus 1. While further research is needed to establish the students' reasoning, in this specific case it may be because of the explanation of the sign of a phase shift in the preparation for the new laboratory: the signals there explicitly start earlier/later. While it was also used in the original lab manual at campus 1, the students now specifically encountered it already during their preparation. The reason why students did this is most likely that some students think of a phase shift as a later start in time, rather than a start at a different part of the cycle. However, the exact reasoning of students requires further investigation.

## 9.4 Bode plot

Many students during the interviews showed problems with both the construction and the use of Bode plots. Earlier research also revealed that students have problems with Bode plots [83–85] and find it a difficult concept [86]. This despite the central importance they have in electronics, with Bernhard and Carstensen even calling them a 'threshold concept' [83, 84]. However, most of the problems discussed in those studies were related to the relationship between the (mathematical) transfer function of a circuit and the corresponding Bode plot. As the students in this study had to construct a Bode plot from measurements, one of the questions in the questionnaire showed a table with a set of 'measurements' and asked the students to construct a possible Bode plot from these 'measurements' (gain only). The exact question is in Fig. 9.7. The measurements correspond to those of a passive band-pass filter (BPF) with cut-off frequencies at 10Hz and 1kHz. Fig. 9.8 shows an example of a (more or less) correct student answer. The reason to choose a BPF rather than the more familiar low-pass or high-pass filters (LPF or HPF) was to avoid students sketching a correct answer by relying on memory and reproducing a graph they had encountered in a lecture or lab.

An **unknown** circuit consists of only resistors and capacitors. To find out how the circuit behaves, **4 measurements** are done. A different AC-voltage is applied every time. The results are in the table below: the amplitude and frequency of the input signal and the amplitude of the output signal are indicated in the table.

On the axes below, draw a possible **Bode plot** for these measurements.

Don't forget to label the axes!

| **Measurement** | $V_{in}$ [V] | $f_{in}$ [Hz] | $V_{uit}$ [V] |
|---|---|---|---|
| **1** | 1 | 1 | 0,100 |
| **2** | 1 | 10 | 0,707 |
| **3** | 10 | 1 000 | 7,071 |
| **4** | 10 | 10 000 | 1,000 |

*Figure 9.7: Bode plot question*

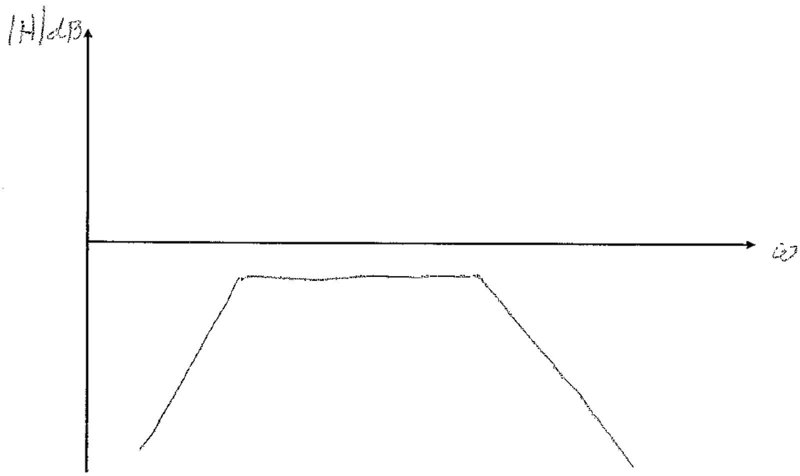



*Figure 9.8: Correct answer to the Bode plot question: a band-pass filter (BPF).*

### 9.4.1 Results

As mentioned above, a more or less correct student answer can be found in Fig. 9.8. Most students however, gave an incorrect answer, the most common of which are shown in Fig. 9.9. These include students who sketched a curve corresponding to a low- or high-pass filter, an example of which is shown in Fig. 9.9b. Others sketched different curves that were still Bode plots, such as a band-stop filter (BSF) shown in Fig. 9.9a or different filters together as in Fig. 9.9c. The remaining students either only labelled their axes or sketched still something else, e.g. a set of signals as in Fig. 9.9d. An overview of the different answers to this question is in Table 9.9.

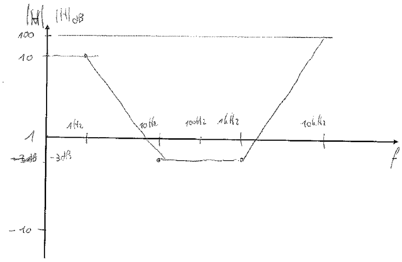
After the original laboratory, only one out of four students answered this question with a sketch corresponding to a band-pass filter. Before the lab, the results were even worse at campus 1 and 2. The biggest group of students then actually sketched a curve corresponding to a low- or high-pass filter, which they had encountered during lectures and labs. In other words, they probably relied on memory when encountering the term 'Bode plot' and clearly had no notion of its underlying idea, namely to provide a representation of the filter gain in dB as a function of (logarithmic) frequency.

At campus 2, there was not much difference after following the new version of the laboratory, although the results were worse before the lab than the year before.

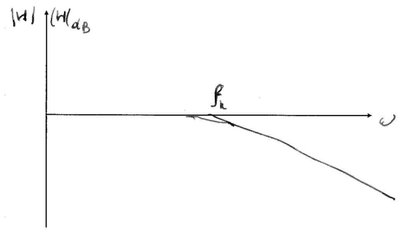
*Table 9.9: Results of Bode plot question (original, pilot and final black box) at all campuses.*

| | # students | | BPF (%) | | LPF/HPF (%) | | Filter(s) (%) | | Other (%) | | Axes (%) | | Blank (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Campus | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post | Pre | Post | | |
| 1 $^{o}$ | 87 | 74 | 6 | 18 | 30 | 26 | 7 | 3 | 16 | 18 | 11 | 14 | 30 | 23 |
| 2 $^{o}$ | 13 | 11 | 54 | 27 | 8 | 18 | 8 | 18 | 0 | 9 | 8 | 18 | 23 | 9 |
| 3 $^{o}$ | 81 | 71 | 12 | 28 | 28 | 42 | 6 | 5 | 14 | 9 | 26 | 3 | 14 | 11 |
| 1 $^{p\ *}$ | 16 | 37 | 6 | 30 | 31 | 8 | 0 | 6 | 25 | 44 | 6 | 3 | 31 | 11 |
| 1 $^{p}$ | 21 | 20 | 62 | 45 | 0 | 25 | 0 | 0 | 24 | 10 | 5 | 5 | 10 | 15 |
| 2 $^{p}$ | 9 | 9 | 22 | 33 | 0 | 22 | 0 | 11 | 11 | 0 | 33 | 33 | 33 | 0 |
| 1 $^{f}$ | 84 | 79 | 50 | 42 | 6 | 23 | 4 | 4 | 20 | 17 | 10 | 8 | 11 | 6 |
| 3 $^{f}$ | 93 | 87 | 9 | 49 | 6 | 20 | 3 | 2 | 15 | 16 | 17 | 5 | 49 | 8 |

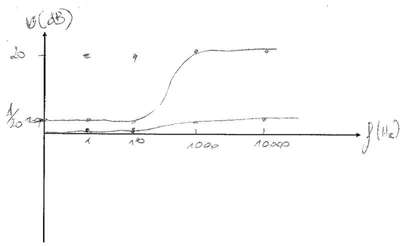
$^{o}$ Original laboratory
$^{p}$ Pilot version of black box laboratory
$^{f}$ Final version of black box laboratory
$^{*}$ Unprepared students



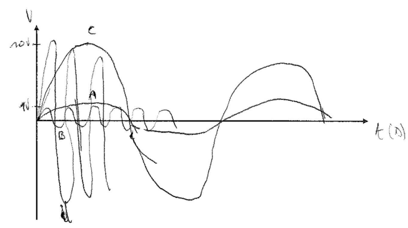
(a) BSF



(b) LPF



(c) 2 filters



(d) signals

*Figure 9.9: Overview of incorrect answers to the Bode plot question. 9.9a is a bandstop filter and 9.9b is a low-pass filter, while other students thought the different input signals would result in different Bode plots, see 9.9c. All of these are examples of incorrect answers that are still a Bode plot. 9.9d is a collection of various signals. In addition to the examples shown, some students only labelled their axes (not necessarily correctly) and others did still something else or left the question blank altogether. This is a repetition of Fig. 4.8.*

We have no explanation for this, since there was no difference in preparation at that campus. However, there were very few students participating in the study at this campus, so most likely it is just a coincidence. At campus 1, there were some interesting observations to be made. The first was the difference between the prepared and unprepared students before the laboratory. While there was virtually no difference between the unprepared students and the students before the original laboratory, the prepared students had clearly understood very well what a Bode plot is. Not only did over 60% of them give a correct answer, but none of them sketched an LPF or HPF characteristic they were familiar with from their lectures. This was not that surprising, as one of the tasks in the preparation focused on exactly this: sketching a Bode plot from a set of (dummy) measurements. After the laboratory session itself, the unprepared students managed a lot better, also compared to the students after the original laboratory. After the lab, more prepared students gave an incorrect answer than before the start of the lab, although they still outperformed their unprepared colleagues (and the students who followed the original laboratory). This indicates that the initial result was indeed mainly due to the preparation and although a part of the students 'forgot' what they had learned, most clearly remembered.

A similar observation could be made before and after the final version of the black box laboratory at campus 1: the students performed very well before the laboratory, after they have prepared for it, but the performance drops after the lab. This time the drop was less pronounced and the students still did better than they did after the original laboratory. At campus 3, the students did not perform better before the lab than their colleagues who followed the original laboratory. This is most likely because they were not prepared yet at the time the survey was administered: at this campus, the questionnaire was administered during the last lecture before the laboratory sessions started, instead of at the beginning of the laboratory due to the short duration of the lab session. However, after the laboratory session (for which they did prepare) they performed at a level similar to that of the (prepared) students at campus 1. At campus 3, the number of students who sketched an LPF or HPF (and relied on memory) halved after following the black box laboratory compared to the original laboratory. The proportion of students sketching an LPF or HPF after attending the black box laboratory is the same as that campuses 1 and 2.

### 9.4.2 Discussion

It is clear that the preparation for the new laboratory helped the students to construct a Bode plot. This influence is evident from the results at campus 3: here, the pre-test was administered at the end of a lecture prior to the lab sessions. As a result, not many of the students had prepared for the lab already, so it is hardly surprising that their performance was no different from the students in the original labs. The results at campus 1 just before the lab also show the distinction between the prepared and unprepared students: the prepared ones did a lot better. While the good result on the pre-test may be linked to short-term memory effects, it is encouraging that the results remain positive a month after the lab session itself. Combined with the results for the unprepared students at the pilot version of the black box laboratory at campus 1, the positive post-test results indicate that the increased understanding of Bode plots is not only due to the preparation, but also due to the design of the black box laboratory itself.

## 9.5 Low-pass filter with varying input signal

### 9.5.1 Question and answer

During the interviews, most students could not draw a circuit of a filter when asked to do so. Moreover, they struggled when trying to answer what would happen to a signal applied at the input of the circuit they had drawn. Therefore, the questionnaire contained a question that showed three circuit diagrams of first order low-pass filters with different input signals. The students were then asked to rank the circuits according to the resulting output voltage and to explain their answer. This allowed both to verify whether or not students recognise the circuit diagram of a first-order low-pass $RC$-filter and to see how they analyse the relation between the input and output signals. The full question is in Fig. 9.10. The correct answer is that $V_{out,B} > V_{out,A} > V_{out,C}$. This can be obtained in various ways. The first is to recognise the circuit as a low-pass filter, which means that the DC signals will be passed undisturbed, while the AC signal will be attenuated. Another way is to replace the capacitor by a short in AC and by an open circuit in DC. Yet another approach is using a voltage divider, replacing the capacitor by its impedance ($Z_C = \frac{1}{j\omega C}$) and filling in zero for the DC frequency.

### 9.5.2 Analysis and results

The analysis of the students' answers was done in two ways. The first was only based on the ranking the students gave. Over 85% of the answers were limited to 5 unique rankings, with other rankings occurring in 5% of the cases or less. The latter were aggregated into the 'Other' category. The second classification was based on the students' explanations. The categories used for those emerged bottom-up from the students' answers as described in Section 5.4.3. An overview of the students' rankings and explanations is in Tables 9.10 till 9.12.

When analysing the results of the students after following the black box laboratory, it became clear the fraction of students who answered this question correctly is the same as the fraction who did so after attending the original laboratory. This was verified using a Z-test, and none of the differences were significant even at the $\alpha$=0.05 level. Similarly, there was no difference between students' answers before and after the laboratory at any of the lab types or campuses according to a binomial test, again not even at the $\alpha$=0.05 level.

When analysing the explanations the students gave, it became clear that the students mainly used classical circuit laws to arrive at a correct answer before

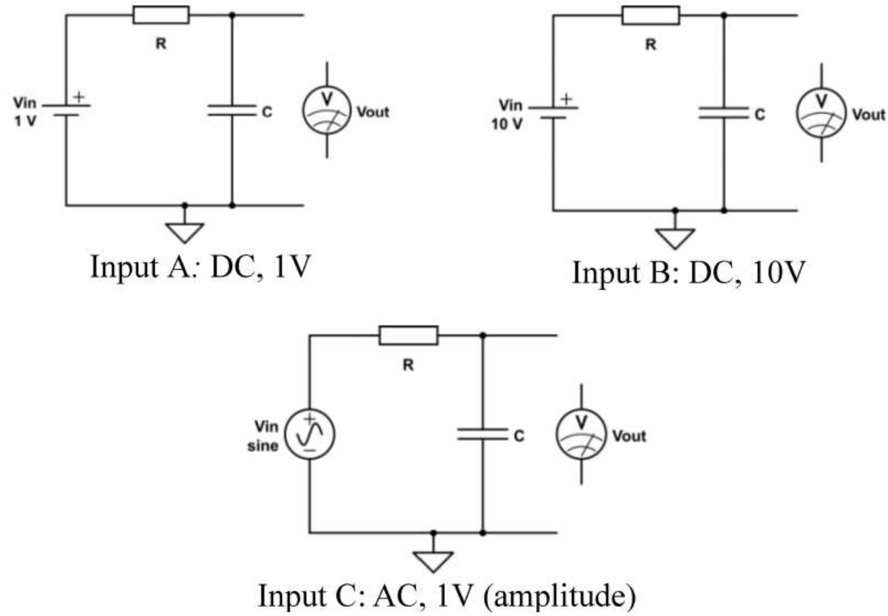



*Figure 9.10: Low-pass filter question. The correct answer is that B>A>C.*

attending the original laboratory: they used a voltage divider or replaced the capacitor by an open switch or short in DC or AC, respectively. However, many students made mistakes when using these circuit laws, even when arriving at a correct answer. Only very few students recognised the circuit as a filter and built their reasoning from there. However, those who did, usually did so correctly. The same pattern emerged after following the original laboratory session: most students used circuit laws but made mistakes, while hardly any recognised the circuits as filters.

These problems with circuit laws remained also when students attended any version of the black box laboratory, both before and after the lab. However, when comparing the pre- and post-test, there are significantly more students who recognised the circuit as a filter after attending the black box laboratory at both campuses 1 and 3. Nevertheless, this was mainly the case not because the students performed much better after the laboratory, but rather because they did worse before the start of the black box laboratory compared to the students before the original laboratory. That being said, it is still the only lab that showed a significant increase when comparing pre to post.

When studying the relationship between the ranking students gave and the explanations they provided, it is immediately clear that many students did not provide any explanation with their ranking. However, there was no difference in the distribution of the rankings of students who did provide an explanation and those who did not according to a $\chi^2$-test. Therefore, it is reasonable to assume that the reasoning of the students who did not provide an explanation is similar to those who did.

A first observation is that the students arrived at a correct answer in many different ways, including using an incorrect approach (e.g. via the RMS value). For the incorrect answers on the other hand, there was a clear connection between a certain answer and the explanation given in two cases. The first was the group of students who thought that C>A=B: nearly all arrived at this answer using the (incorrect) current-based reasoning approach. Similarly, those who answered that B>A=C usually thought so because they did not distinguish between AC and DC signals and simply ignored the circuit altogether. These two observations occured in both the pre- and post-tests of all laboratories (original and black box).

### 9.5.3 Conclusion

Overall, the black box laboratory did not improve the students' performance on this question. One noteworthy observation is that after the black box laboratory, at least in its final form, there was a significant increase in the number of students who recognised the circuit as an $RC$-filter when comparing pre- and post-test. However, this was mainly because there were less students who recognised the circuit as a filter in the pre-test compared to the number of students who recognised the filter at the start of the original laboratory, making it hard to compare both groups adequately.

## 9.6 High-pass filter with varying components

### 9.6.1 Question and answer

During the student interviews, students not only failed to predict what would happen when different signals were applied to a circuit, but they also did not manage to judge what would happen when the components of the circuit were changed. The last question discussed here probed the students about this problem. It showed several high-pass $RC$-filters (HPF), with a constant

*Table 9.10: Results of LPF question in the original laboratories. The columns refer to the ranking of the circuits as shown in Fig. 9.10 while the rows are the explanations given by the students. All numbers are absolute values, so number of students.*

| | | **B>A>C** | **C>A=B** | **B>A=C** | **C>B>A** | **B>C>A** | **Other** | **Blank** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|
| PRE-TEST | Filter | 13 | 2 | 0 | 3 | 0 | 1 | 0 | **19** |
| | Open/Short | 5 | 0 | 0 | 0 | 0 | 0 | 0 | **5** |
| | Voltage divider | 2 | 0 | 0 | 0 | 0 | 1 | 0 | **3** |
| | CBR | 0 | 6 | 0 | 1 | 0 | 2 | 0 | **9** |
| | AC=DC | 0 | 0 | 8 | 0 | 0 | 1 | 0 | **9** |
| | RMS | 10 | 3 | 0 | 0 | 2 | 0 | 0 | **15** |
| | Other | 8 | 2 | 1 | 4 | 0 | 4 | 0 | **19** |
| | No explanation | 39 | 19 | 1 | 10 | 11 | 8 | 0 | **88** |
| | Blank | 0 | 0 | 0 | 0 | 0 | 0 | 14 | **14** |
| | **TOTAL** | **77** | **32** | **10** | **18** | **13** | **17** | **14** | **181** |
| POST-TEST | Filter | 10 | 1 | 0 | 1 | 0 | 1 | 0 | **13** |
| | Open/Short | 8 | 0 | 0 | 0 | 0 | 0 | 0 | **8** |
| | Voltage divider | 6 | 0 | 0 | 0 | 0 | 0 | 0 | **6** |
| | CBR | 0 | 4 | 0 | 0 | 0 | 1 | 0 | **5** |
| | AC=DC | 2 | 0 | 8 | 0 | 0 | 1 | 0 | **11** |
| | RMS | 5 | 0 | 0 | 0 | 2 | 0 | 0 | **7** |
| | Other | 8 | 0 | 1 | 0 | 2 | 0 | 0 | **11** |
| | No explanation | 39 | 8 | 6 | 5 | 13 | 15 | 0 | **86** |
| | Blank | 0 | 0 | 0 | 0 | 0 | 0 | 9 | **9** |
| | **TOTAL** | **78** | **13** | **15** | **6** | **17** | **18** | **9** | **156** |

*Table 9.11: Results of LPF question in the pilot laboratories. The columns refer to the ranking of the circuits as shown in Fig. 9.10 while the rows are the explanations given by the students. All numbers are absolute values, so number of students.*

| | | **B>A>C** | **C>A=B** | **B>A=C** | **C>B>A** | **B>C>A** | **Other** | **Blank** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|
| PRE-TEST | Filter | 1 | 0 | 0 | 0 | 0 | 0 | 0 | **1** |
| | Open/Short | 8 | 2 | 0 | 0 | 0 | 0 | 0 | **10** |
| | Voltage divider | 2 | 0 | 0 | 0 | 0 | 0 | 0 | **2** |
| | CBR | 0 | 2 | 0 | 0 | 0 | 1 | 0 | **3** |
| | AC=DC | 0 | 1 | 3 | 0 | 0 | 0 | 0 | **4** |
| | RMS | 1 | 0 | 0 | 0 | 0 | 0 | 0 | **1** |
| | Other | 2 | 0 | 0 | 1 | 1 | 0 | 0 | **4** |
| | No explanation | 10 | 1 | 0 | 5 | 1 | 2 | 0 | **19** |
| | Blank | 0 | 0 | 0 | 0 | 0 | 0 | 2 | **2** |
| | **TOTAL** | **24** | **6** | **3** | **6** | **2** | **3** | **2** | **46** |
| POST-TEST | Filter | 8 | 0 | 0 | 0 | 0 | 0 | 0 | **8** |
| | Open/Short | 9 | 2 | 0 | 0 | 1 | 1 | 0 | **13** |
| | Voltage divider | 6 | 0 | 0 | 0 | 0 | 0 | 0 | **6** |
| | CBR | 0 | 4 | 0 | 0 | 0 | 0 | 0 | **4** |
| | AC=DC | 0 | 0 | 9 | 0 | 0 | 1 | 0 | **10** |
| | RMS | 1 | 0 | 0 | 0 | 0 | 0 | 0 | **1** |
| | Other | 1 | 0 | 0 | 0 | 1 | 1 | 0 | **3** |
| | No explanation | 11 | 1 | 0 | 2 | 4 | 2 | 0 | **20** |
| | Blank | 0 | 0 | 0 | 0 | 0 | 0 | 1 | **1** |
| | **TOTAL** | **36** | **7** | **9** | **2** | **6** | **5** | **1** | **66** |

*Table 9.12: Results of LPF question in the final laboratories. The columns refer to the ranking of the circuits as shown in Fig. 9.10 while the rows are the explanations given by the students. All numbers are absolute values, so number of students.*

| | | **B>A>C** | **C>A=B** | **B>A=C** | **C>B>A** | **B>C>A** | **Other** | **Blank** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|
| PRE-TEST | Filter | 2 | 1 | 0 | 0 | 0 | 0 | 0 | **3** |
| | Open/Short | 18 | 1 | 0 | 1 | 0 | 0 | 0 | **20** |
| | Voltage divider | 11 | 0 | 0 | 0 | 0 | 0 | 0 | **11** |
| | CBR | 0 | 3 | 0 | 0 | 1 | 1 | 0 | **5** |
| | AC=DC | 1 | 0 | 15 | 0 | 0 | 0 | 0 | **16** |
| | RMS | 11 | 0 | 1 | 0 | 2 | 0 | 0 | **14** |
| | Other | 4 | 1 | 0 | 1 | 2 | 1 | 0 | **9** |
| | No explanation | 47 | 6 | 3 | 7 | 12 | 9 | 0 | **84** |
| | Blank | 0 | 0 | 0 | 0 | 0 | 0 | 15 | **15** |
| | **TOTAL** | **94** | **12** | **19** | **9** | **17** | **11** | **15** | **177** |
| POST-TEST | Filter | 12 | 3 | 2 | 0 | 0 | 2 | 0 | **19** |
| | Open/Short | 13 | 3 | 0 | 0 | 0 | 0 | 0 | **16** |
| | Voltage divider | 7 | 1 | 0 | 0 | 0 | 0 | 0 | **8** |
| | CBR | 0 | 1 | 0 | 1 | 0 | 1 | 0 | **3** |
| | AC=DC | 2 | 0 | 10 | 0 | 0 | 1 | 0 | **13** |
| | RMS | 10 | 0 | 2 | 0 | 8 | 0 | 0 | **20** |
| | Other | 5 | 1 | 0 | 0 | 0 | 1 | 0 | **7** |
| | No explanation | 42 | 7 | 5 | 4 | 7 | 5 | 0 | **70** |
| | Blank | 0 | 0 | 0 | 0 | 0 | 0 | 10 | **10** |
| | **TOTAL** | **91** | **16** | **19** | **5** | **15** | **10** | **10** | **166** |

(finite) AC input signal but doubled (or halved, depending on the questionnaire) component values. The exact question is in Fig. 9.11.

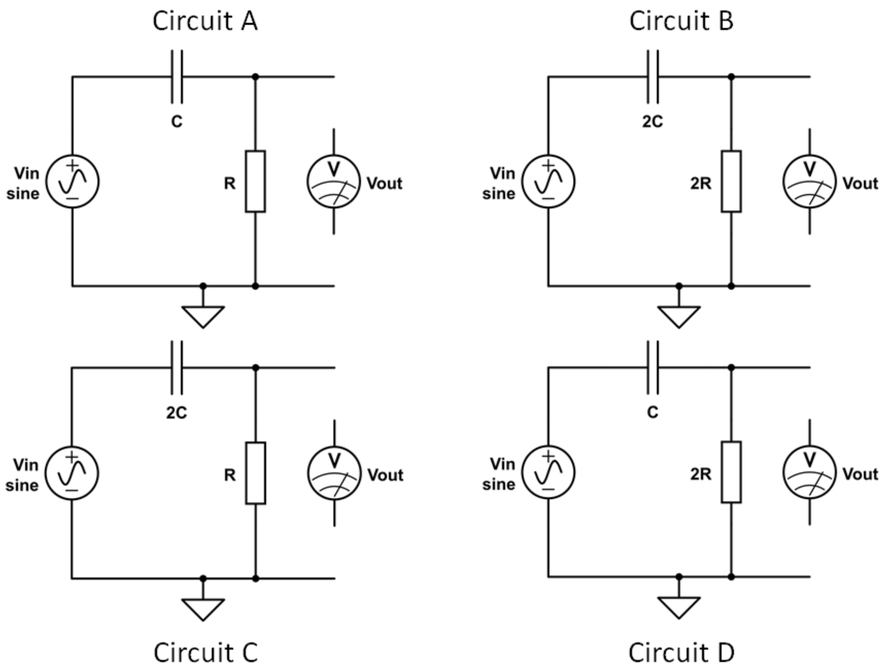



*Figure 9.11: High-pass filter question. The correct answer in this case is that B>C=D>A. With halved instead of doubled components, the correct answer would be that A>C=D>B.*

The correct answer is that $V_{out,B} > V_{out,C} = V_{out,D} > V_{out,A}$. Again, this can be analysed in various ways, of which the first one uses the fact that this circuit is a high-pass filter (HPF). As shown in Fig. 9.12, this can be most easily done by using the Bode plot of a first order high-pass $RC$-filter. When looking at circuits A and D for example, one can deduce that the cut-off frequency of circuit D will be half that of circuit A ($f_c = \frac{1}{2\pi RC}$). Consequently, the Bode plot of circuit D will 'shift to the left' with respect to that of circuit A, which in turn leads to a higher gain at a certain frequency $f$ for circuit D. This higher gain means that for a constant input amplitude, the output amplitude of circuit D will also be higher than that of circuit A. Using the same approach for all 4 circuits, the Bode plots for circuits C and D coincide, while B will be shifted even more to the left. This leads to the correct solution.

A second approach is to look at the circuit as a voltage divider: $v_{out} = \frac{Z_R}{Z_C+Z_R} v_{in}$.

Since $Z_C = \frac{1}{j\omega C}$ and $Z_R = R$, it is clear that (when all other parameters are kept constant) the output voltage increases if the resistor increases, as well as when the capacitor value increases. Not only that, but doubling the resistor has the same effect as doubling the capacitor. This again leads to the conclusion that circuit B will have the highest output voltage (doubling both the resistor and the capacitor results in an even higher output voltage), followed by circuit C and D and finally circuit A with the lowest output voltage.

It is also possible to explicitly use classical circuit laws (Kirchhoff's laws and Ohm's law), arriving at the same conclusion. The voltage divider approach discussed earlier is essentially a short-cut of this approach.

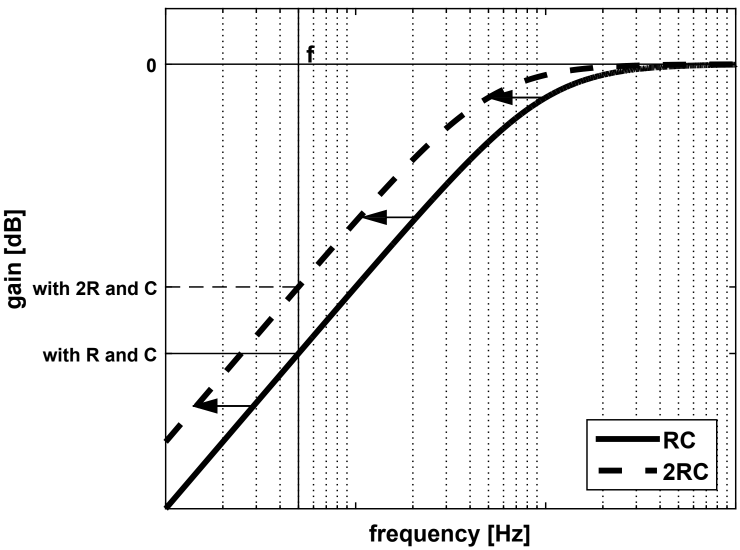



*Figure 9.12: Explanation of high-pass filter question. The solid line represents the Bode plot of a circuit with a resistor with value R and a capacitor with value C, configured as a high-pass filter. Doubling the resistor (or capacitor) will result in a Bode plot that is shifted to the left (dashed line), with respect to the original one. At a certain frequency f, the gain (so also the output voltage for an equal input voltage) will then be higher for the circuit with the increased resistor. This is a repetition of Fig. 5.4.*

### 9.6.2 Analysis and results

As with the low-pass filter question discussed in Section 9.5 above, the student answers were categorised in two ways: one based on the given ranking and one based on the given explanation. The approach used to define the categories for the explanations is the same as the one used for the LPF question and is explained in more detail in Section 5.5.3. The categorisation of the actual ranking given on the other hand, is done in a slightly different way. Because there are too many possible options to rank 4 circuits, the categorisation was done pairwise. 4 pairs were most relevant: the comparison of the 'original circuit' with resistor value 'R' and capacitor value 'C' (circuit A) to the other three circuits, and the comparison of circuits C and D (in which one of both components is changed). This is the same approach described in Section 5.5.3.

As in the analysis of the original labs, the discussion here does not make any distinction between different campuses, only between different types of laboratory (original lab, pilot version of the black box lab and final version of the black box lab). The results of the rankings as well as the explanations the students provided are in Tables 9.13 till 9.15. During the original laboratories, it became clear that students knew very well that doubling the capacitor and/or resistor would have an influence on the output voltage (see Table 9.13). However, they did not know what the *direction* of this change would be. Moreover, they did not realise that the *magnitude* of the change in output voltage would be the same for a doubling (or halving) of resistor and of capacitor value. The same was still true for the black box laboratories as is clear from Tables 9.14 and 9.15: there is no significant change in the answering patterns. Students still knew that changing either component would have an influence on the output voltage, but they did not know the direction or (relative) size of that influence. This is somewhat surprising, as the switch aspect of the black box laboratory explicitly covered a circuit with a change in component values.

When analysing the different explanations given by the students, it is again important to note that there was a large number of students who did not provide any explanation with their answer. Moving the question forward in the survey did little to increase the number of students who gave an explanation, nor to decrease the number of blank answers. But as with the LPF question, there was no difference in the rankings provided by the students who gave an explanation and those who did not. Therefore, it is reasonable to assume that the train of thought of the students who did not provide an explanation was similar to that of those who did. There was no striking change in the strategies the students (attempted to) used to solve this question when comparing the original laboratories to the black box labs, except in the number of students who used classical circuit laws without using a voltage divider. There was no difference between the number of students using this approach before the original laboratory and either version of the black box labs. However, this number nearly tripled after following the final version of the black box laboratories while it stayed constant after the original laboratories and pilot version of the black box labs.

One other aspect stood out when looking at the relationship between the explanations and the rankings. After attending either version of the black box laboratory, the students who recognised the circuits as filters knew very well that circuits C and D (with only one of the components doubled or halved) would have the same output voltage. They knew this much better than other students who attended the same labs but used a different approach and also than the students who used the same approach after attending the original laboratory. However, those students (who recognised the filter after the black box labs) failed to compare the other pairs correctly. A possible train of thought that could explain this observation is the following. The students knew that the cut-off frequency will play a role in the output voltage. Therefore, they knew that two circuits with the same cut-off frequency would have the same output voltage. When two circuits have a different cut-off frequency, they also knew that the output frequencies of both circuits would be different. What they did not know, however, was the type of influence of the cut-off frequency: the did not know whether an increase in cut-off frequency would cause a decrease in output voltage or vice versa.

### 9.6.3 Conclusion

As with the low-pass filter question, there was no increase in the number of correct answers to this question after following the black box laboratory. Contrary to the LPF question however, there was also no increase in the number of students who recognised the circuits as high-pass filters after the laboratory compared to before. On the other hand, there was an increase in the number of students who used classical circuit laws after the final version of the black box laboratory, both when comparing it to the original laboratory and to the pre-lab results. In addition, the students were also more successful than before when using this approach. When looking at the students who did recognise a filter, the data suggests that those students reasoned more by using the cut-off frequency after following a black box laboratory. This reasoning is not always correct, however.

*Table 9.13: Results of HPF question in the original laboratories. The columns refer to the ranking of the circuits as shown in Fig. 9.11 while the rows are the explanations given by the students. All numbers are absolute values, so number of students.*

| | | **D>A** | **D=A** | **D<A** | **No info** | **C>A** | **C=A** | **C<A** | **No info** | **B>A** | **B=A** | **B<A** | **No info** | **C=D** | **C<D** | **C>D** | **No info** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PRE-TEST | Filter | 11 | 2 | 7 | 3 | 13 | 0 | 7 | 3 | 11 | 0 | 3 | 9 | 16 | 1 | 1 | 5 | **23** |
| | Voltage divider | 11 | 0 | 5 | 1 | 8 | 0 | 8 | 1 | 3 | 7 | 4 | 3 | 2 | 8 | 7 | 0 | **17** |
| | Circuit laws | 6 | 0 | 3 | 0 | 6 | 0 | 3 | 0 | 2 | 0 | 0 | 7 | 0 | 3 | 6 | 0 | **9** |
| | Only R matters | 6 | 0 | 0 | 1 | 1 | 5 | 1 | 0 | 1 | 1 | 0 | 5 | 0 | 6 | 0 | 1 | **7** |
| | Only C matters | 1 | 4 | 0 | 0 | 3 | 0 | 2 | 0 | 1 | 0 | 1 | 3 | 0 | 2 | 3 | 0 | **5** |
| | Other | 0 | 1 | 4 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 3 | 2 | 1 | 3 | 1 | 0 | **5** |
| | No explanation | 47 | 1 | 37 | 5 | 42 | 1 | 42 | 5 | 32 | 3 | 27 | 28 | 12 | 41 | 34 | 3 | **90** |
| | Blank | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 25 | 0 | 0 | 0 | 25 | **25** |
| | **TOTAL** | **82** | **8** | **56** | **35** | **73** | **6** | **68** | **34** | **50** | **11** | **38** | **82** | **31** | **64** | **52** | **34** | **181** |
| POST-TEST | Filter | 4 | 0 | 5 | 0 | 5 | 0 | 4 | 0 | 6 | 0 | 3 | 0 | 3 | 4 | 2 | 0 | **9** |
| | Voltage divider | 9 | 0 | 5 | 0 | 7 | 0 | 7 | 0 | 3 | 6 | 5 | 0 | 3 | 6 | 5 | 0 | **14** |
| | Circuit laws | 0 | 0 | 3 | 1 | 1 | 0 | 2 | 1 | 1 | 2 | 1 | 0 | 0 | 1 | 2 | 1 | **4** |
| | Only R matters | 5 | 0 | 3 | 0 | 3 | 3 | 2 | 0 | 5 | 0 | 3 | 0 | 0 | 5 | 3 | 0 | **8** |
| | Only C matters | 2 | 1 | 2 | 1 | 4 | 1 | 1 | 0 | 4 | 0 | 2 | 0 | 0 | 1 | 5 | 0 | **6** |
| | Other | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| | No explanation | 47 | 0 | 46 | 5 | 35 | 2 | 57 | 4 | 40 | 15 | 39 | 4 | 11 | 55 | 30 | 2 | **98** |
| | Blank | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | **17** |
| | **TOTAL** | **67** | **1** | **64** | **24** | **55** | **6** | **73** | **22** | **59** | **23** | **53** | **21** | **17** | **72** | **47** | **20** | **156** |

*Table 9.14: Results of HPF question in the pilot laboratories. The columns refer to the ranking of the circuits as shown in Fig. 9.11 while the rows are the explanations given by the students. All numbers are absolute values, so number of students.*

| | | D>A | D=A | D<A | No info | C>A | C=A | C<A | No info | B>A | B=A | B<A | No info | C=D | C<D | C>D | No info | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PRE-TEST | Filter | 1 | 0 | 1 | 3 | 2 | 0 | 2 | 1 | 2 | 0 | 2 | 1 | 2 | 0 | 0 | 3 | **5** |
| | Voltage divider | 0 | 0 | 0 | 4 | 2 | 2 | 0 | 0 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 4 | **4** |
| | Circuit laws | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | **1** |
| | Only R matters | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| | Only C matters | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| | Other | 3 | 0 | 0 | 3 | 6 | 0 | 0 | 0 | 5 | 0 | 1 | 0 | 2 | 1 | 0 | 3 | **6** |
| | No explanation | 1 | 0 | 0 | 19 | 10 | 3 | 6 | 1 | 11 | 2 | 6 | 1 | 0 | 0 | 1 | 19 | **20** |
| | Blank | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 10 | 0 | 0 | 1 | 9 | 0 | 0 | 0 | 10 | **10** |
| | **TOTAL** | **5** | **0** | **1** | **40** | **21** | **5** | **8** | **12** | **20** | **2** | **13** | **11** | **4** | **1** | **1** | **40** | **46** |
| POST-TEST | Filter | 6 | 0 | 3 | 1 | 5 | 0 | 4 | 1 | 6 | 0 | 4 | 0 | 8 | 2 | 0 | 0 | **10** |
| | Voltage divider | 11 | 0 | 3 | 1 | 8 | 3 | 3 | 1 | 8 | 2 | 5 | 0 | 5 | 6 | 4 | 0 | **15** |
| | Circuit laws | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | **1** |
| | Only R matters | 8 | 0 | 1 | 0 | 5 | 2 | 2 | 0 | 6 | 3 | 0 | 0 | 1 | 5 | 2 | 1 | **9** |
| | Only C matters | 1 | 2 | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | **3** |
| | Other | 4 | 0 | 2 | 0 | 3 | 0 | 3 | 0 | 3 | 0 | 3 | 0 | 5 | 1 | 0 | 0 | **6** |
| | No explanation | 10 | 0 | 4 | 1 | 7 | 2 | 5 | 1 | 5 | 2 | 7 | 1 | 2 | 7 | 5 | 1 | **15** |
| | Blank | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 7 | 0 | 0 | 0 | 7 | **7** |
| | **TOTAL** | **40** | **2** | **14** | **10** | **31** | **7** | **18** | **10** | **31** | **7** | **20** | **8** | **22** | **21** | **14** | **9** | **66** |

*Table 9.15: Results of HPF question in the final laboratories. The columns refer to the ranking of the circuits as shown in Fig. 9.11 while the rows are the explanations given by the students. All numbers are absolute values, so number of students.*

| | | **D>A** | **D=A** | **D<A** | **No info** | **C>A** | **C=A** | **C<A** | **No info** | **B>A** | **B=A** | **B<A** | **No info** | **C=D** | **C<D** | **C>D** | **No info** | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PRE-TEST | Filter | 4 | 0 | 9 | 0 | 3 | 1 | 9 | 0 | 3 | 0 | 10 | 0 | 8 | 2 | 3 | 0 | **13** |
| | Voltage divider | 28 | 0 | 10 | 1 | 18 | 0 | 20 | 1 | 15 | 17 | 7 | 0 | 7 | 21 | 9 | 2 | **39** |
| | Circuit laws | 9 | 0 | 1 | 0 | 3 | 0 | 7 | 0 | 5 | 1 | 3 | 1 | 0 | 7 | 2 | 1 | **10** |
| | Only R matters | 7 | 1 | 1 | 0 | 4 | 0 | 5 | 0 | 8 | 0 | 1 | 0 | 0 | 8 | 1 | 0 | **9** |
| | Only C matters | 6 | 1 | 4 | 0 | 6 | 0 | 5 | 0 | 5 | 0 | 6 | 0 | 0 | 5 | 6 | 0 | **11** |
| | Other | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 2 | 0 | 0 | **2** |
| | No explanation | 42 | 4 | 26 | 4 | 34 | 7 | 32 | 3 | 35 | 11 | 26 | 4 | 5 | 37 | 30 | 4 | **76** |
| | Blank | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | 0 | 0 | 0 | 17 | **17** |
| | **TOTAL** | **97** | **7** | **51** | **22** | **68** | **8** | **80** | **21** | **71** | **30** | **54** | **22** | **20** | **82** | **51** | **24** | **177** |
| POST-TEST | Filter | 5 | 0 | 8 | 1 | 4 | 0 | 9 | 1 | 4 | 0 | 9 | 1 | 13 | 0 | 1 | 0 | **14** |
| | Voltage divider | 15 | 0 | 4 | 2 | 11 | 0 | 8 | 2 | 8 | 5 | 5 | 3 | 3 | 14 | 3 | 1 | **21** |
| | Circuit laws | 19 | 1 | 7 | 2 | 12 | 0 | 16 | 1 | 13 | 5 | 9 | 2 | 5 | 15 | 7 | 2 | **29** |
| | Only R matters | 11 | 0 | 3 | 0 | 2 | 4 | 8 | 0 | 9 | 1 | 4 | 0 | 0 | 10 | 4 | 0 | **14** |
| | Only C matters | 4 | 2 | 1 | 0 | 3 | 0 | 4 | 0 | 3 | 0 | 4 | 0 | 0 | 4 | 3 | 0 | **7** |
| | Other | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| | No explanation | 37 | 2 | 29 | 2 | 17 | 2 | 49 | 2 | 28 | 15 | 26 | 1 | 11 | 44 | 14 | 1 | **70** |
| | Blank | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 11 | 0 | 0 | 0 | 11 | **11** |
| | **TOTAL** | **91** | **5** | **52** | **18** | **49** | **6** | **94** | **17** | **65** | **26** | **57** | **18** | **32** | **87** | **32** | **15** | **166** |

## 9.7 Discussion

In general, there was no great increase in the learning outcome of the black box laboratory compared to the original laboratory that could be detected with the conceptual questionnaire used in this study. The only exception was the construction of a Bode plot from a set of given data. Most likely, this was due to the addition of a pre-lab exercise about Bode plots in combination with reinforcement during the lab itself.

When sketching a signal with two frequencies or sketching a signal with a phase shift, there was even a decrease in student performance compared to the original laboratory. This could be because in the black box laboratory, there was no emphasis on measuring the phase shift during the lab session itself.

There are signs that students who attended the black box laboratory recognised a low-pass filter more often than after the original laboratory, but they did not answer the low-pass filter question any better (or worse, for that matter) after attending the black box laboratory compared to the original laboratory. When it comes to the high-pass filter question, it was surprising that there was a big increase in the number of students who used an approach based on circuit laws. While there was no increase in the number of students using a filter-based approach in this case, those who did seemed to know that the cut-off frequency plays an important role in the behaviour of a filter. However, they did not know what exactly this role is.

# Chapter 10

# Conclusion

**Context**

In this dissertation, an electronics lab session on first order $RC$-filters was studied in detail, with a four-fold goal. The first was to evaluate whether or not learning concepts was a goal of electronics laboratories according to both teachers and students. The second was to investigate student understanding of first order $RC$-filters. A third goal was to study student activities and verbalisations during the laboratory sessions. The fourth and last goal was to find a way to improve the conceptual learning in the laboratory session. This final chapter starts with a summary of the findings and answers to these research questions. In a second part, we will discuss the implications of the project for laboratory education. In the third and final section, we will consider some limitations of the work and address perspectives for future research.

## 10.1 Rationale

Although laboratories play a very important role in engineering education, as testified by, for example, the large fraction of face-to-face time assigned to them in curricula, relatively little research exists on educational advantages or limitations of laboratory instruction in engineering education. Moreover, laboratories are typically expensive in terms of equipment and staff time. Therefore, we set up a research project to extend our knowledge on student learning in lab courses. During the course of an engineering curriculum however, there are many labs that are very different in terms of subject matter (chemistry, biology, physics, computer programming, $\cdots$), level (from introductory demonstration labs in the first year to specialised preparation for a master's thesis) and type (practising safety procedures, observing a principle, learning measurement processing, designing a program, $\cdots$). It is very hard to compare such a wide and diverse range of settings, which is why the project was limited to one specific lab: the electronics lab on first order $RC$-filters. The choice for an introductory electronics lab on first order passive $RC$-filters was made because there already exists a fair body of literature on introductory electricity, but not much is known about students' knowledge or understanding of more advanced electronics concepts. $RC$-filters are on the border between both, since the circuits themselves are typically studied in introductory physics courses as (dis)charging capacitors and are reintroduced in subsequent introductory electronics courses as filters.

The general aim of the project was to find out if "*engineering technology students learn concepts in an electronics laboratory about first order RC-filters*" and whether we "*can improve their learning.*" To do so, we conducted several studies. The first, described in Chapter 2, investigated the goals of the laboratory to verify that learning concepts was indeed an aim of this lab. Secondly, the students' conceptual understanding of filters was investigated using interviews (described in Chapters 3 and 7) and a conceptual questionnaire (see Chapters 4 and 5). To study student behaviour in the lab sessions themselves, groups of students were videotaped during their lab sessions and the recordings were subsequently analysed. This study is described in Chapter 6. The conclusions from the interviews, the questionnaire and the video analysis were used to develop a new laboratory session, described in detail in Chapter 8. This new laboratory was subsequently evaluated using the same video analysis and questionnaire as were used to study the original laboratories. The results are in Chapter 6 and 9 respectively.

These studies yielded various results that merit specific attention. This chapter provides a short overview of the most significant results and offers some suggestions for future research and for more effective laboratory education.

## 10.2 Conclusions of the study

### 10.2.1 Student and staff ideas on lab goals

We decided to research engineering students' (conceptual) learning in laboratories because laboratories constitute a significant part of the curriculum in that field, and in electronics in particular. Before looking at student learning however, it is important to clarify what the intended object of learning is for these laboratories. So as a first step in the research, we asked students what they thought their teachers' lab goals were. This was especially important since the goals of laboratories in general are not well-defined in literature [7, 10, 152]. Some even argue that the lack of research in the field of laboratory education is (partially) due to a lack of consensus about the learning objectives [7]. In the field of electronics, there is no established literature discussing the goals of laboratory education to our knowledge. Therefore, we did a survey among both teachers and students to document the goals of laboratories in an introductory electronics course. This will provide a reference for the research into the actual lab sessions themselves. The survey among students was necessary to ensure that they understood their teachers aims for the laboratory, an important condition for learning [10–13]. As a general conclusion, teachers and students agreed that the main goal of the laboratory is to increase students' understanding of theory, so conceptual understanding. There were two main points of disagreement however: the teachers also found critical reflection about measurements and proper reporting important, while students put more emphasis on learning practical skills in laboratories. The conclusions from this study may help in the design and/or evaluation of introductory electronics laboratories. For the specific research project discussed in this dissertation, the study confirmed that deepening conceptual understanding is an important aim of laboratory education and is as such a valuable research topic.

In the specific case of the laboratory of $RC$-filters, the learning goals as specified by the lab manuals were threefold. After the lab sessions, the students should

- understand the behaviour of first order $RC$-filters;
- be able to work with the lab equipment (function generator and oscilloscope);
- know how to construct and read Bode plots.

Full details are in Chapter 2.

### 10.2.2 Student understanding of first order *RC*-filters

Given the conclusion of the study on the goals (which showed that learning concepts is a main goal of laboratory education), the second study of the project focused on students' understanding of first order $RC$-filters. This topic was chosen because it is at the transition between physics and electronics in the sense that students already encounter this circuit in the context of charging and discharging capacitors in a preceding physics course (about which some literature exists [57, 75, 76]), but analyse it using AC signals for the first time in introductory electronics courses. As such, $RC$-circuits also serve as an introduction to various concepts widely used in electronics, including filters and analysis in the frequency domain via Bode plots. For this reason, $RC$ filters are a very popular topic for introductory electronics laboratories: the lab is taught at all campuses of the faculty of engineering technology of the KU Leuven we investigated. While there has been a lot of research into student problems with so-called 'bulbs and battery' circuits (e.g. Refs. [65, 66, 69]), there is only limited research on student understanding of more advanced electronics topics such as AC-circuits or filters. Likewise, the research about Bode plots is scarce and is usually from a system theory perspective: the construction of Bode plots from a transfer function, not as a practical relation of the output signal to the input signal as a function of frequency [83, 85, 86].

To gauge student understanding of $RC$-circuits (used as filters) and associated topics, we started by conducting a series of interviews with students [96]. Besides other interesting findings, three aspects of $RC$-filters that are important during laboratory sessions also proved difficult for the interviewed students: signal properties (frequency and phase), Bode plots and the circuits themselves. From these interviews, a conceptual questionnaire was developed to verify how widespread the problems and misconceptions encountered in the interviews were. The questionnaire contained questions about signals (discussed in Chapter 4) and about circuits (discussed in Chapter 5). It was administered to second year engineering technology students at three different campuses. From the interviews and the subsequent conceptual questionnaire, three major conclusions with respect to students' conceptual understanding could be drawn.

The first one is that students do not have a problem understanding what a *phase shift* is, although they do struggle with its *direction* or sign (see Section 4.4.1 and 4.5.1). This means that the problems students have with phase shift that were observed in literature as well as in the interviews (see 3.4.5), such as ignoring the phase shift caused by $RC$-filters or thinking a phase shift is between two voltages instead of between voltage and current, are most likely not due to a misconception about phase itself, but rather about the *cause* of this phase shift [59, 77, 78, 82, 109–111].

Second, students demonstrated a wide range of problems when trying to answer ranking questions about first order $RC$-filters. As suspected, many of the problems the students had are also prevalent in literature about students' problems with DC circuits, including:

- *Current-based reasoning*: Students tend to reason primarily based on current, rather than potential (or voltage) [66, 68]. Many students consequently interpreted Ohm's law incorrectly, stating that "there is no current, hence no voltage." While the statement about current is correct, the subsequent conclusion about voltage is not. See Sections 3.4.1 and 5.4.3.
- *Local reasoning*: Several studies observed that students often only look at the effect of a change in the circuit around the place where this change happened, rather than taking the entire circuit into account [62, 66, 84]. This was especially visible in the question about the high-pass filters (HPF's), where students were asked to rank the output voltage of HPF circuits with varying components but the same input voltage. Some students thought only the resistor would have an influence on the output voltage, while changing the capacitor would not impact it all. See Section 5.5.3 for more details.

While many of the problems described above have been described in literature before (albeit sometimes in a different context), there are also some important new findings:

- *Little recognition of a circuit as a first order RC-filter*: This happens even after specific (laboratory and lecture) instruction on those filters. Instead, most students used circuit laws to arrive at a correct answer (or tried to). Around 75% of those who do recognise the filters are able to answer the question about low-pass filters, as opposed to less than half of those who use a different approach (see Section 5.6).
- *Ignoring frequency*: Especially with the low-pass filter question, some students did not even consider the frequency as a factor that would influence the behaviour of the circuit, see Section 5.4.3.

- *Misconceptions about capacitors in AC*: While students who think the output only depends on the resistor for a high-pass filter could be suffering from local reasoning, the ones who think that only the capacitor has an influence, have one of two different misconceptions. They are either stuck on the idea that a capacitor will not influence the amplitude (but only the phase) of a signal or that the resistor does not influence AC-signals. Section 5.5.3 gives more details.

Finally, many students did not understand the *underlying concept of a Bode plot*, namely that it is a representation of the output signal of a system with respect to its input signal as a function of frequency. The students in our study did not manage to construct a Bode plot based on a set of measurements, even after attending the laboratory session where this was an explicit task, see Section 4.4.3. This is different from literature, where students typically fail to construct a Bode plot based on a transfer function by relating its poles and zeroes to the slope of the function or fail to predict the output signal of a filter given the input signal and a Bode plot of the filter [83, 85, 86]. After attending the black box laboratory however, the results in students' Bode plot construction improved markedly, see Section 9.4.

### 10.2.3 Conclusions related to the laboratory sessions

After the goals and the questionnaire, several conclusions with respect to the third aspect of the study, the laboratory itself, are discussed in this section. Both the problems that were found during the original laboratory and how they led to changes in the new laboratory as well as the effects of this new laboratory are discussed.

By observing the students during lab sessions using video-analysis, it became clear that students spent little time discussing concepts in the original labs. Instead, a lot of time was spent manipulating equipment and performing measurements. This was also confirmed during the interviews, where students indicated they learned most after the laboratory session, when processing their data at home. We suspect this is due to the students suffering from cognitive overload during the laboratory: they are overwhelmed by several new aspects of electronics at once including the measuring equipment (it is the first time they use an oscilloscope or function generator), the $RC$-filters themselves and the Bode plots. Although this observation of students being overwhelmed is not new [44, 152], current teaching practise does not counter it yet.

In addition to the problems caused by the cognitive overload, the students suffered from confirmation bias: their manuals contained example measurements or at least a pre-defined set of frequencies at which to perform measurements. The filter the students measured was also known to them in advance. Consequently, they did not think about a suitable measurement grid (for which conceptual understanding is needed), nor did they evaluate their measurements critically after performing them during the laboratory as they already know what to expect. This is further hindered by the fact that they did not process any measurements (by constructing Bode plots) and did not perform any simulation during the laboratory.

Based on these observations as well as the outcomes of the conceptual questionnaire and the interviews, a new laboratory was developed. The adjustments to the lab focused on two aspects: reducing the cognitive overload by moving some aspects (oscilloscope reading and Bode plots) to a compulsory preparation and removing confirmation bias by using black boxes instead of known circuits. The first exercise in the preparation asked students to construct a Bode plot based on a set of (simulated) measurements. The second consisted of a Matlab simulation of an oscilloscope, in which the students could practise oscilloscope configuration and reading before making an exercise about it. The students were asked to hand in both exercises (about the Bode plot and the oscilloscope reading) at the beginning of the laboratory session.

Using black boxes as a teaching tool is not a new idea [131, 132], but has not often been studied in literature to our knowledge, with the exception of one study where students reported they thought a black box lab on Thévenin equivalent circuits helped them to understand the underlying concepts better [133]. In our case of the $RC$-filter lab, the students were handed a unique 'black box' and were told it contained a resistor and capacitor from a given list, configured as either an LPF or HPF. Their task was then to determine the contents of the box by using a function generator, Ohm meter and, most importantly, an oscilloscope. They had to determine not only the configuration of the components (HPF or LPF), but also their specific values. A second aspect of the lab used ideas from variation theory [50, 53, 147]: each black box had a switch that would add a component (resistor or capacitor) of the same value as the original component to the circuit either in series or parallel with the original component. In addition to that information, the students also received the Bode plot corresponding to the circuit with the extra component. They were then asked to determine which component was added and in what configuration, using the given Bode plot as well as the equipment available from the first task (function generator, oscilloscope and Ohm-meter).

When looking at students' activities and verbalisation during the lab (‘effectiveness 1’), the ‘black box’ laboratory had a positive impact. An important observation in that respect is that the *preparation helped* in various ways. The first aspect is the use of the oscilloscope: students spent noticeably less time performing measurements (or managed to gather more in the same amount of time), freeing time to discuss and interpret the gathered measurements. Secondly, they managed to read and interpret the given Bode plot (compare it to their measurements) properly. The time gained by spending less on measuring was spent mostly on interpreting and discussing the data, or in other words: more conceptual knowledge discussion. This was a clear improvement over the original labs, where there was no discussion or even processing of measurement results. Changing the circuit by using the switch also helped to discuss the underlying concepts very clearly. However, it did not usually take long for the students to figure out what had happened and this was mostly analysed in a mathematical way. A final aspect that most likely contributed to this effect was the elimination of the confirmation bias by presenting the students with an unknown instead of a known circuit and removing measurement examples from the manual. Removing the example set of measurements and initial frequencies also helped to trigger meaningful discussion about which measurement point to choose next based on an understanding of previous measurement outcomes.

As mentioned above, the new laboratory did not contribute much to an increase in learning outcomes after the lab (‘effectiveness 2’), except for the construction of a Bode plot from a given set of measurements. The latter was done much better after making the preparation. This was not only the case when entering the lab (and it was still fresh in their minds from making the preparation), but persisted till one month after the laboratory session as was evident from the results of the post-tests. This was only the case for students who had prepared for the laboratory: students who attended the black box laboratory without preparing for it did not show an increased competence in sketching Bode plots compared to the students who followed the original laboratory. However, neither the prepared nor the unprepared students showed evidence of recognising the filters in the questionnaire any more after taking the black box laboratory than they did after taking the original laboratory, nor did they answer the questions about filters better by using other approaches. Also the answers to the other questions related to signals did not improve.

This dual result raises an important question regarding the model for learning in laboratories shown in Fig. 1.1 and discussed in Section 1.3 as well as in literature [29, 30, 33]. According to this model, there is a link between students’ activities during the laboratory session and the eventual learning outcomes. However, our observations indicate that a major difference in student activities during the lab did not result in a dramatic change in learning outcomes, at least not according to the answers the students gave in our questionnaire. In other words: there was no evidence of the connection between an increased 'effectiveness 1' and the 'effectiveness 2' of the laboratory when it came to the understanding of first order passive $RC$-filters.

That being said, the laboratory clearly does address the concern often voiced in literature that laboratories are too much 'cookbook' style and do not stimulate student discussion or thinking [10, 18, 19, 33, 36, 44, 46, 134, 152]. In addition, moving two new aspects away from the lab room to a preparation seemed to help lower the cognitive load on students during the laboratory session itself observed in other studies as well as our own (see Chapter 6) [44, 152].

## 10.3 Discussion

When interpreting the results discussed in Section 10.2 and in the dissertation in general, it is important to keep some aspects of the research in mind. Below are some comments, arranged per topic.

### 10.3.1 Student ideas about goals

In Chapter 2 the goals of a laboratory according to students and teachers are compared. This was done using a survey, where participants could score a list of 17 goals on a Likert scale and had to rank the 5 goals they thought most important. This list of 17 goals was based on earlier research about what *staff* thought were relevant goals, as well as on the lab manuals in the specific laboratories investigated in this study. Although none of the students added a goal to the list (which was possible), it still means that the goals of the survey are added from a teacher's perspective, but not from a student's perspective. This and other aspects warrant a more thorough discussion of the findings of Chapter 2. A first issue that arises due to this is that there may be goals left out that the students did find important, but could not adequately formulate in the survey.

A second aspect has to do with the interpretation of a goal: it is possible students and teachers interpret the specific meaning of certain goals differently, such as what 'theory' is or what 'technical aspects' are. A final aspect, related to the previous one, is the terminology used. In the introduction, the idea of concepts was introduced in Section 1.5, as opposed to procedural learning. Because it was unlikely students (or teachers) were familiar with terms such as 'concepts' or 'procedural knowledge', terms such as 'theory' and 'practical applications' were used instead. However, those terms are not equivalent and it is not certain participants in the survey interpret them in the same way that was intended. Therefore, the conclusion that both teachers and students agree that conceptual learning is the most important aspect of a laboratory may be too far fetched based on the available data. That being said, the general assumption of the study that increasing conceptual understanding is an important goal of laboratories is certainly still valid, as the goals listed are those closest to conceptual understanding (and no others emerge as more important), while the goals stated for the laboratory sessions in the manuals include conceptual goals as well.

### 10.3.2 Bode plots

In the entire dissertation, Bode plots have been called an important 'concept' when learning about electronics. When discussing the question about Bode plots, the task was referred to as 'constructing' a Bode plot from a given set of measurements, which is more representative of a procedural task. In fact, Bode plots (and especially the way in which they were treated in this dissertation) are the *representation* of the underlying concept of frequency-dependency. So they are not themselves concepts, but are a way of graphically showing how the input and output of a circuit are related to each other and to the frequency. This idea of frequency-dependency certainly is one of the most important concepts in electronics as a whole, with Bode plots being the main way of visualising them.

### 10.3.3 Alignment between questionnaire and laboratory

Despite the good results of the black box laboratory in the video study, the outcomes of the conceptual questionnaire are somewhat underwhelming. They indicate that some student problems persist despite an improved 'effectiveness 1' of the laboratory. This first of all raised the question of what the link is between both types of effectiveness, as discussed in Section 10.4.6 below. But it is also possible to take a closer look at the questions themselves to gain a better idea of the reason behind the low post-test scores for both types of laboratory, especially about the filter-related questions.

The first of these questions (see Section 5.4.1 or 9.5.1) essentially asked the students to compare the output of a low-pass filter for a DC input signal and an AC input signal. A possible explanation for the low fraction of students who answered this question correctly (just over 50% in most laboratories) is that during none of the laboratories, the students were explicitly asked to apply a

DC signal to their circuit to observe what happened. Although they did apply AC input signals with varying frequencies, it may be a step too far (far transfer [153]) for students to associate a DC signal with a frequency equal to zero.

The second question related to filters (see Section 5.5.1 or 9.6.1) asked about the influence of the component values on the output signal of a high-pass filter when the input signal is a constant sine wave. Although the black box laboratory does explicitly ask about what happens when a component is changed, it only asks about the influence this has on the Bode plot. Again, it may be too hard for the students to transfer a change in Bode plot to a change in output signal (for the same input signal), or a change in component value directly to a change in output value.

Neither of these points undermines the conclusions of the earlier discussions about these questions (presented in Sections 5.6 and 9.7), as they did serve to uncover various student problems that are not addressed by any version of a laboratory studied in this dissertation. These points do mean that there is no one-on-one relation between the questions asked in the questionnaire and what happens in the laboratory, which was meant to prevent so-called 'teaching to the test'. It would be very interesting to develop a more detailed test, that probes all aspects of the laboratory, as discussed in Section 10.4.2 below.

## 10.4 Suggestions for future research

The project presented and discussed above brought several aspects to light that merit further investigation. Unfortunately, many of these topics were beyond the scope of this dissertation. They are presented below, including some aspects that were covered during the project, but could be improved upon.

### 10.4.1 Participants

The overall scope of the research was limited to students of the Faculty of Engineering Technology at the KU Leuven. Due to practical constraints, only students at 3 campuses participated. While the sample size especially for the conceptual questionnaire and the survey about goals was adequate, the participating students were all from the same field. Consequently, it is not possible to extend the conclusions to students from other fields of study such as engineering science or physics, to non-Belgian students or to students of a different level. A straightforward solution to this limitation is to extend this type of research to a broader student audience as well as field of study.

A related aspect not explored in this study are the teachers themselves. While they had of course seen the questionnaire and the black box laboratory and gave informal feedback, the teachers did not fill in the questionnaire or try out the lab. Additionally, the teachers were not interviewed about their specific intentions with the laboratory. It would certainly be interesting to compare the students' results to the questionnaire and behaviour in the lab to that of their teachers and/or other experts as has been done in other studies [154, 155].

### 10.4.2 Conceptual questionnaire

While the questions in the questionnaire helped to reveal many problems and misconceptions students held, it is not a fine-tuned instrument to measure students' conceptual understanding. As discussed in Section 10.3.3, it may not be suitable enough to accurately measure student learning after the laboratory, for example. Although the questions certainly have their merits, there is only one question per topic and the interpretation of a students' answer in terms of conceptual understanding depends on the explanation (s)he provides. The reason for this was the limited time available to administer the test (10 to 15 minutes at the beginning of a lab or at the end of a lecture). Using this questionnaire served to reveal interesting aspects of student thinking, which should be further explored. A way to do this that was beyond the scope of the research project, is to develop the questionnaire further to become a real concept inventory in the style of the well-established Force Concept Inventory (FCI) or other, similar inventories [55, 60, 156].

As this was, to our knowledge, the first questionnaire about $RC$ filters, there is not only room for improvement of the form of the questionnaire, but there are also several conclusions related to the topic itself that deserve more research. The two questions about a low- and high-pass filter asked in the conceptual questionnaire indicated that *some students think in terms of filters* about a circuit, while others approach it using circuit laws. Although both approaches are equally suitable in this specific situation, it would be interesting to find out why one is sometimes preferred over the other and whether or not students switch their preference over the course of their education. Additionally, it would be interesting to expand the research to include students from other fields (e.g. physics majors) and/or (engineering) experts into the study.

In the phase-related question of the questionnaire, a sizeable fraction of the students sketched a signal that started later (or sometimes earlier) in time than the given signal (see Section 4.4.1). We suspect that this is due to the students thinking about a phase shift as a signal starting later in time, rather than a signal starting at a different place in a cycle. While both approaches are correct in the context of the question, informal discussion with the TA's indicated that students have problems when it comes to the phase shift of a high-pass filter. They typically think that the output signal for a low-pass filter has a negative phase shift with respect to the input signal because it takes time for a change in the input to advance to the output. There is only anecdotal evidence for this misconception, but as there are also indications of time-based thinking about phase in the conceptual questionnaire and other problems with phase discussed in literature, this specific aspect calls for further investigation [77, 78, 157].

### 10.4.3 Video analysis

By focusing the video-recording on only one pair of students per class, it was possible to analyse their behaviour and verbalisation in depth. However, this time-consuming approach limited the number of students being studied. To make sure the data still covered as broad a range as possible within this limit, the participants were selected randomly (as opposed to using volunteers) and different classes were analysed (instead of videotaping all students in a single class for example).

The methodology used to analyse the videos is not without flaws either. Some of them were listed in the original project [33]:

- *Exact timing*: The division of the lab time in 30 second intervals is rather arbitrary. This can lead to some activities that start halfway a slot to sometimes be coded in the first slot and sometimes in the second one. This does not have any influence on the results or conclusions of the study presented in this dissertation, but can be an issue if one wants to use this methodology in a setting where exact timing is more important. An other problem is that only the dominating activity can be coded, while it is possible that two or more activities happen in one time slot, for example a very short intervention by the TA. It is possible to adjust the approach by either using smaller time intervals or by using a flexible time interval for each activity. However, either approach would nullify the advantage of the current approach to do a near real-time analysis of the data, making the analysis process much lengthier.

- *Overlapping categories*: Especially in terms of verbalisations, it is sometimes hard to differentiate between different categories, as is testified by the rather low agreement between different raters. This is also related to the timing issue: when does one category end and another begin?

Again using a smaller time interval could help with this, although some categories may remain troublesome, such as the difference between talking about conceptual knowledge or mathematical knowledge, as much depends on the interpretation of the coder.

- *Verbalisation as knowledge verbalisation*: All statements the students make are interpreted as verbalisation of a certain type of knowledge (unless of course, it is clearly unrelated to the content). However, not all verbalisation is necessarily an expression of one's knowledge, but could also be, for example, an observation or guess.

Even if the verbalisation refers to a student's real knowledge, an increase in student verbalisation of knowledge does not necessarily imply that the student is also actively *thinking*: the knowledge can be remembered or even unconcious. Another limit of using verbalisation as a measure of students' mental activity is that only the knowledge that is verbalised is encoded: tacit knowledge that may be used by the students or his (her) exact thoughts are still hidden.

A final limit of the approach used is that there is no judgement of the '*quality*' of a certain verbalisation. A statement that is categorised as 'content knowledge' for instance, could be a statement of a misconception or the verbalisation of a (correct) insight by the students. Another example is the reading of a measurement, which can be done correctly or incorrectly. Therefore, the video data could be analysed using a different or more elaborate coding set, taking also the 'quality' of the verbalisations or actions into account. This could lead to a more detailed understanding of specific student problems or reasoning patterns.

### 10.4.4 Research into 'reverse engineering' teaching

As mentioned, the idea of using 'black boxes' as an educational tool is not new [131, 132], but the impact on student learning of using them has not been investigated (or investigated in a limited fashion [133]) in literature to our knowledge. The results of this approach in the present study are encouraging, mainly because it eliminates confirmation bias in labs where the students "merely observe something they already know" [152]. This makes it interesting to investigate whether the same approach can be used in different settings. This is of course not limited to electronics or even engineering, but could be extended to other fields such as natural sciences, computer science, medicine or even social sciences.

### 10.4.5 The oscilloscope simulator

Students' problems with oscilloscopes have also been observed by other authors and seem to be an important obstacle for proper student learning during the laboratory [130]. An important stumbling block is that the problems with the oscilloscope shifts the students' attention from the content of the laboratory to working with the oscilloscope. Our method of preparing the students by using a simulator seems to help a great deal to improve the students' versatility with this (in electronics) important piece of equipment. However, it is not clear how students use it exactly and what further improvement could be made. Another area of improvement is more technical: the simulator is currently written in Matlab, which is available to the students only at their university and not at home. It is also not the most appropriate programming language to gather data and feedback about how students use the simulator, nor does it facilitate easy distribution to students. Therefore, it should be reprogrammed to make it suitable as e.g. a webpage that can be ran from a browser or a small program that does not require the Matlab 'parent' environment. A first step could be to convert the Matlab root programme into an executable file that can be ran independently.

In a more general perspective, replacing laboratories by simulations has been tried before [25, 62, 158, 159]. There is also some research about the comparison of a simulated preparation versus a written preparation, during which it was found that students were generally prepared better using a simulation of the 'big picture' of their (mechanics) lab [159]. However, our research suggests that students benefit from preparing for laboratories by using a simulated version of an important piece of lab equipment. This improvement by using a simulated version of equipment to practise deserves further research, especially in areas where safety is an important concern.

### 10.4.6 Relation between laboratory activities and learning outcome

In the model for learning in a laboratory presented in the introduction (see Section 1.3), there are two types of effectiveness of a laboratory [29, 30]. The 'effectiveness 1' is the relation between actual student activities during the lab session and the teachers intended student activities. 'Effectiveness 2' on the other hand is the relation between the eventual learning outcomes and the teachers' learning objectives for the laboratory. Moreover, there is a supposed relation between the student laboratory activities and the eventual learning outcome. From the video analysis, the black box laboratory clearly differed from the original laboratory in terms of the students' activities during the lab (effectiveness 1). However, there was very little change in the learning outcome after the lab (effectiveness 2). The latter was clear from the student answers to the questionnaire, especially to the questions about the $RC$-filters themselves. This begs the question what the precise relation is between student activities during the laboratory and eventual student learning, as a clear difference in laboratory activity did not cause a change in conceptual learning outcome. This corresponds to other research that also showed that (secondary school) students tend to recall specific, observable aspects of their laboratories, but fail to connect them to underlying principles and ideas [30].

As laboratories are often used to enhance students' conceptual understanding, the nature and indeed the existence of the link between student activities in the laboratory and the eventual conceptual learning results has to be analysed in more depth. That being said, our research also indicated an increase in a more procedural aspect (constructing Bode plots), even long term. An interesting outcome was also that only in the new laboratory, the students displayed better understanding of the construction of Bode plots, which may be an indication that laboratory behaviour does influence more procedural learning, but not conceptual learning. This potential of laboratories as a tool to enhance students' more procedural knowledge deserves more research especially since our research was limited to a rather narrow field. Expanding it to other subject areas and/or majors (where the laboratory aim could be different) may shed more light on this difference in learning outcomes.

## 10.5 Suggestions for teaching

In practical terms, our research has shown that students perform better *during* the lab with our adjustments. However, they still did not show an increased conceptual understanding of the subject matter. Therefore, we think laboratories are not the most suitable approach to teach (relatively) new concepts to students. This does not imply that laboratories are unsuitable in teaching, but rather that their learning goals should be different from enhancing conceptual understanding.

When designing a new laboratory session or adjusting an existing one, we think it is important to avoid *confirmation bias* and *cognitive overload* for the students. The cognitive load can be lowered by *focusing on one learning goal* during the laboratory. Of course, laboratories are a very complex learning environment, which makes the cognitive load of the students very high even when executing a relatively simple task. A way to decrease the cognitive load is to ask the students to *prepare* for the laboratory. The preparation in our lab focused on two aspects: *measurement gathering* and *measurement processing*. We noticed an improvement during the lab in the students' speed of measuring, which freed time for other activities. This suggests that students greatly benefit from getting acquainted with laboratory equipment already in the preparation.

In addition, giving them the opportunity to practice how to process their measurements with a set of dummy examples helped them to process measurements during the lab, which made it possible to discuss their results more readily. To eliminate confirmation bias, it helped to remove all examples from the manual, as well as to give the students a completely unknown circuit. In addition to eliminating the confirmation bias, we also (informally) observed that using a black box approach challenged the students and triggered them to actively look for the content of the box.

During the interviews, it also became clear that students rarely finished all their work during the laboratory session itself, even when they had enough time. They preferred going home earlier to process their measurements and draw conclusions from them there. However, this often caused problems as their measurements were incomplete or downright wrong. To encourage the students to make at least some preliminary conclusions during the laboratory session itself, we asked them to hand in their measurement results as well as some preliminary conclusion ('the answer') at the end of the laboratory session. This really stimulated the students to finish their measurements, process them and think about them during the laboratory session itself.

## 10.6 Conclusion

From this study about engineering students' learning and activities in laboratories about first order $RC$-filters, several clear conclusions could be drawn. First of all, it is clear that the aim of the laboratories is indeed to teach concepts rather than procedural knowledge. However, both interviews and a conceptual questionnaire showed that there are several problems with students' conceptual understanding. Video observations of the laboratory themselves showed that students spent most of their time on gathering measurements and not on discussing those measurements or the circuits themselves. This was most likely due to a cognitive overload caused by the introduction of many new concepts to the students: Bode plots, lab equipment and, of course, $RC$-filters themselves. In order to decrease this cognitive overload, several changes were made to the laboratory, including adding a preparation and a black box. During this adjusted laboratory, the students indeed spent more time discussing and interpreting measurements instead of only gathering them. However, this change in student behaviour during the laboratory session did not increase the number of correct answers to the conceptual questionnaire. The latter observation raises a question with respect to the relation between student lab activities and the eventual learning outcome. This is an important outcome of the study that deserves further investigation.

# Appendix A

# Survey goals

*The answers to this survey will be treated strictly confidential and will only be used in a scientific study on the perception of students about goals of labs. Reporting will only be done about groups, never about individuals. Your anonymity is fully guaranteed.*

☐ **I agree that my data will be processed confidentially**

| | |
|---|---|
| Student number : | Gender (M/F) : |
| Year and field of study : | Age : |

Below is a list of possible goals for electronics labs. Please indicate how important each one is in your opinion.

Electronics labs serve to …

| | | Not important at all | Not important | Neither important, nor unimportant | Important | Very important |
|---|---|---|---|---|---|---|
| **A** | learn basic practical skills (such as soldering). | | | | | |
| **B** | illustrate the theory of the lectures. | | | | | |
| **C** | learn the functioning of important devices. | | | | | |
| **D** | learn how to interpret and analyse experimental data and measurements. | | | | | |
| **E** | learn how to write a report about an experiment. | | | | | |
| **F** | learn measuring techniques. | | | | | |
| **G** | learn how to come up with an experiment. | | | | | |
| **H** | teach new theory (that was not addressed in the lectures). | | | | | |
| **I** | learn how to handle measurement results critically. | | | | | |
| **J** | get to know practical applications of the theory. | | | | | |
| **K** | learn how to work in a team. | | | | | |
| **L** | learn safety principles. | | | | | |
| **M** | practise the use of conventions and standards (such as colour codes). | | | | | |
| **N** | learn an experimental method as an alternative for a theoretical approach. | | | | | |
| **O** | understand the theory (of the lectures) better. | | | | | |
| **P** | learn how to report orally on an experiment. | | | | | |
| **Q** | learn how to work with simulation software. | | | | | |

Are there any goals that are not in the list above that you would like to add?

What are the most important learning goals in a lab according to you? Rank the 5 most important ones from the list above and fill them in in the table below, starting with the most important one. If for instance, you find goal Z the most important one, write a 'Z' in the first box.

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| | | | | |

Thank you and good luck for the rest of the year!

# Appendix B

# Conceptual questionnaire

Studentnumber: Gender (M/F):

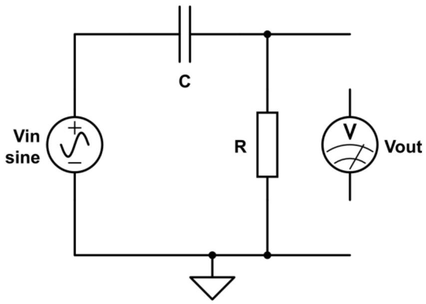
## Question I

The circuits below all have the **same AC-voltage** (finite amplitude and finite frequency) as input signal. However, the **values of the resistor and capacitor are different** in every circuit.

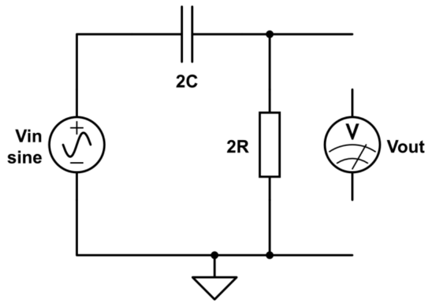
Sort the circuits according to decreasing **amplitude of the output voltage** (highest to lowest). Explicitly indicate if the output voltage is zero or if the output voltage in two situations is equal.

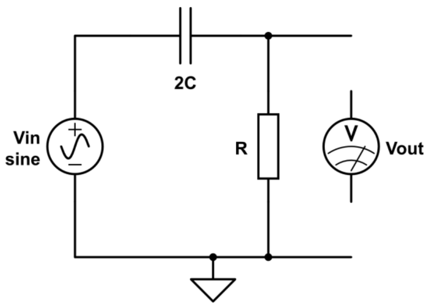
**Explain your answer!**

Circuit A

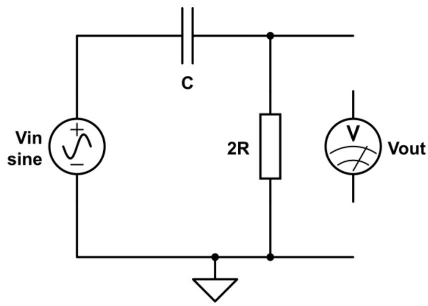



Circuit B




Circuit C



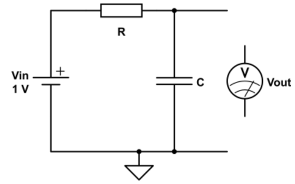

Circuit D

## Question II

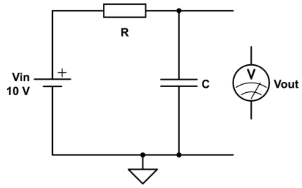
Below are **3 identical circuits**. A **different input voltage** is applied to each one.
After some time, the output voltage is measured.

Sort the circuits according to the **maximum of the output voltage**, from largest to smallest. Indicate explicitly when the output voltage is zero or when two output voltages are equal.

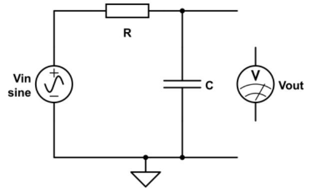
**Explain your answer!**




Input A*:* DC, 1V



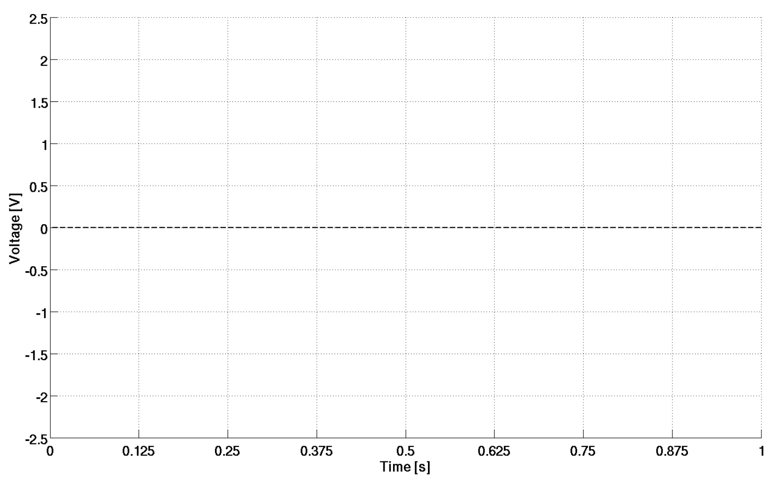

Input B: DC, 10V




Input C: AC, 1V (amplitude)

## Question III

Draw a signal with two frequency components in the axis below!



## Question IV

An **unkown circuit** consists of only resistors and capacitors. To find out how the circuit behaves, **4 measurements** are done. A different AC-voltage is applied every time. The results are in the table below: the amplitude and frequency of the input signal and the amplitude of the output signal are indicated in the table.

On the axes below, draw a possible **Bode plot** for these measurements.

Don't forget to label the axes!

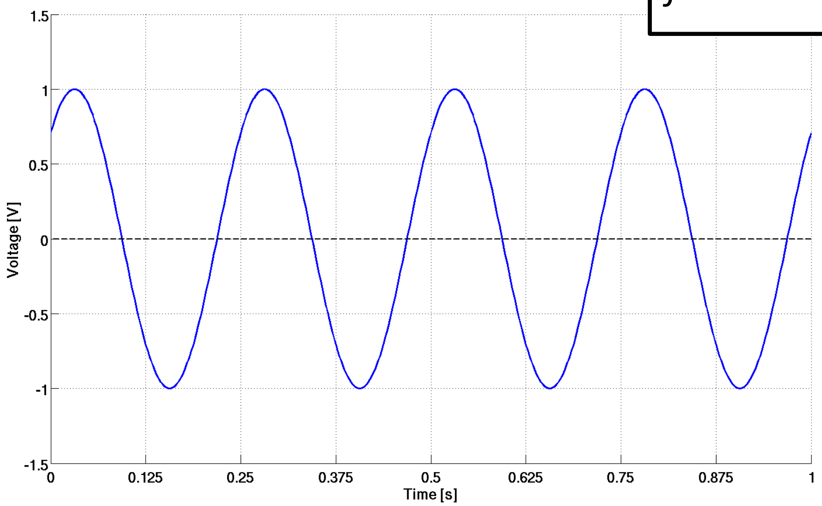
| Measurement | $V_{in}$ [V] | $f_{in}$ [Hz] | $V_{uit}$ [V] |
|---|---|---|---|
| **1** | 1 | 1 | 0,100 |
| **2** | 1 | 10 | 0,707 |
| **3** | 10 | 1 000 | 7,071 |
| **4** | 10 | 10 000 | 1,000 |

## Question V

In the axes below, draw a signal with a frequency twice as high as the given signal.

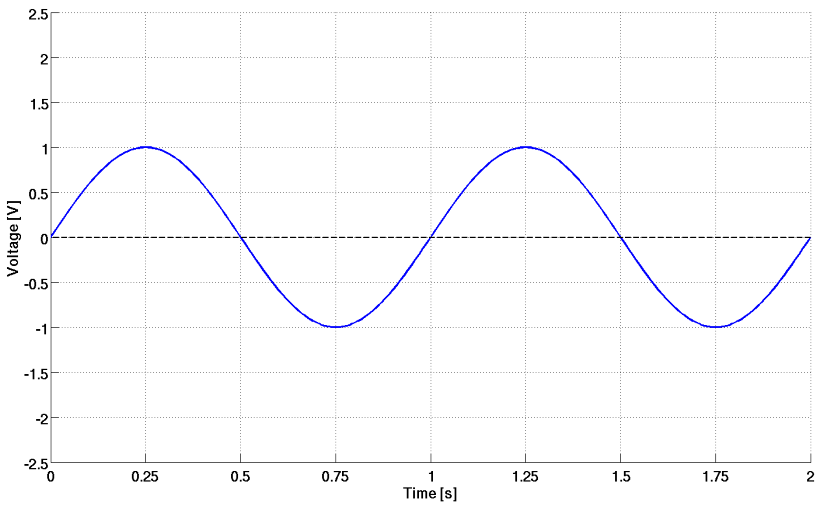
What is the frequency of the original signal?

*f* =




## Question VI

Draw, in the axes below, a signal that leads the given one by 90°.



# Appendix C

# Categories video analysis

*Table C.1: Categories for contexts*

| Code | Name | Explanation | Example | CBAV† | Warren‡ |
|---|---|---|---|---|---|
| O | Other | Things unrelated to the lab | Chat about last night's party | O | Off |
| 3P | Third person | Third person intervenes in the group | The TA comes to answer a question | 3P | TA |
| LG | Labguide | Use the labguide | Check the labguide to verify the set-up | LG | (TA) |
| BB | Blackboard | Explanation to the whole class | The TA introduces the lab | LG | TA |
| WD | Write & discuss | Write and/or discuss | Prepare tables for a measurement | PP | W |
| MA | Manipulate apparatus | Use the lab equipment | Build the circuit | MA | P |
| ME | Measurement | Perform a (routine) measurement | Read the amplitude and write it down | ME | P |
| CB | Build computer model | Construct a simulation model | Make the first SPICE file | CMB | SMD |
| CS | Computer simulation | Run a computer simulation | Run the ac simulation in multisim | CMU | P |
| MP | Process measurement | Routinely process measurements | Convert the gain to dB | CL | P |
| DD | Data discussion | Discuss their measurements | Argue about next measurement point | / | SM |

† As in Niedderer et al [33]
‡ As in Warren [40]

*Table C.2: Categories for verbalization*

| Code | Name | Explanation | Example | CBAV† | Warren‡ |
|---|---|---|---|---|---|
| TK | Technical knowledge | Knowledge related to equipment | Try to find the right button | KT | P(?) |
| CK | Content knowledge | Knowledge about the content matter | Argue whether it is a LPF or HPF | KP | SM |
| TC | Technical & content | Technical and content intertwined | Why connect oscilloscope in parallel | KTP, $KTP_i$ | SM |
| MK | Mathematical knowledge | State a mathematical formula | State the formula for $f_c$ | KM | SMM |
| GD | Geometrical description | Describe data geometrically | "The output voltage increases" | KMM | SM(U) |
| CD | Content-based description | Content-based data interpretation | "This is $f_c$, the phase is $45°$" | KMP/KMT | SM(A) |
| ED | Example-based description | Compare data to an example | "The graph looks like in the manual" | / | / |
| MR | Measurement reading | Read the value of a measurement | "Now the amplitude is $5V$" | / | P |
| NV | No verbalization | No, unclear or irrelevant talk | Discuss last night's party | / | / |

† As in Niedderer et al [33]
‡ As in Warren [40]

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